(12) **UK Patent Application** (19) **GB** (11) **2 308 451** (13) **A**

(21) Application No 9625474.3

(22) Date of Filing 06.12.1996

(30) Priority Data
(31) 08576069   (32) 21.12.1995   (33) US

(71) Applicant(s)
The University of Queensland

(Incorporated in Australia - Queensland)

St Lucia, Queensland 4067, Australia

(72) Inventor(s)
Stuart Crozier
David Michael Doddrell

(74) Agent and/or Address for Service
Batchellor, Kirk & Co
2 Pear Tree Court, Farringdon Road, LONDON,
EC1R 0DS, United Kingdom

(51) INT CL^6
G01R 33/38 33/385 33/3875

(52) UK CL (Edition O)
G1N NG38 NG40 N571

(56) Documents Cited
GB 2070254 A   EP 0304188 A2   WO 96/13045 A1
WO 94/06034 A1   US 4398150 A

(58) Field of Search
UK CL (Edition O) **G1N NG38 NG38A NG40**
INT CL^6 **G01R 33/38 33/3815 33/3875**

(54) **Short bore MRI magnet with some coils carrying reversed current**

(57) Axial MRI magnets designed with the aid of computer-based simulated annealing procedures comprise sets of coils in which some of the coils carry current flowing in the reverse direction. Such reversed flow, in combination with a relatively large number of coils, allows the development of short bore MRI magnets with high field homogeneity. The annealing procedure uses a weighted spherical harmonic field homogeneity error function. The procedures may be applied also to shim and gradient coils, and to the design of effective active shielding. A biplanar magnet is disclosed (figure 10).
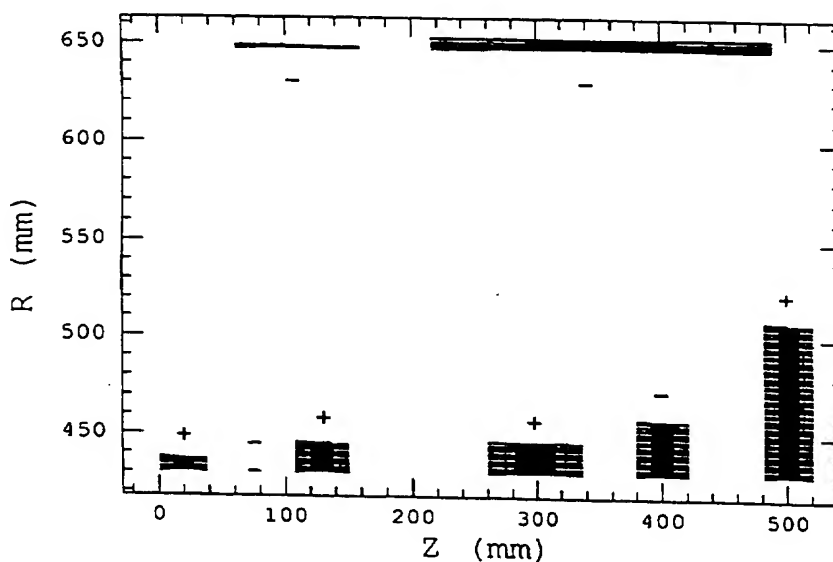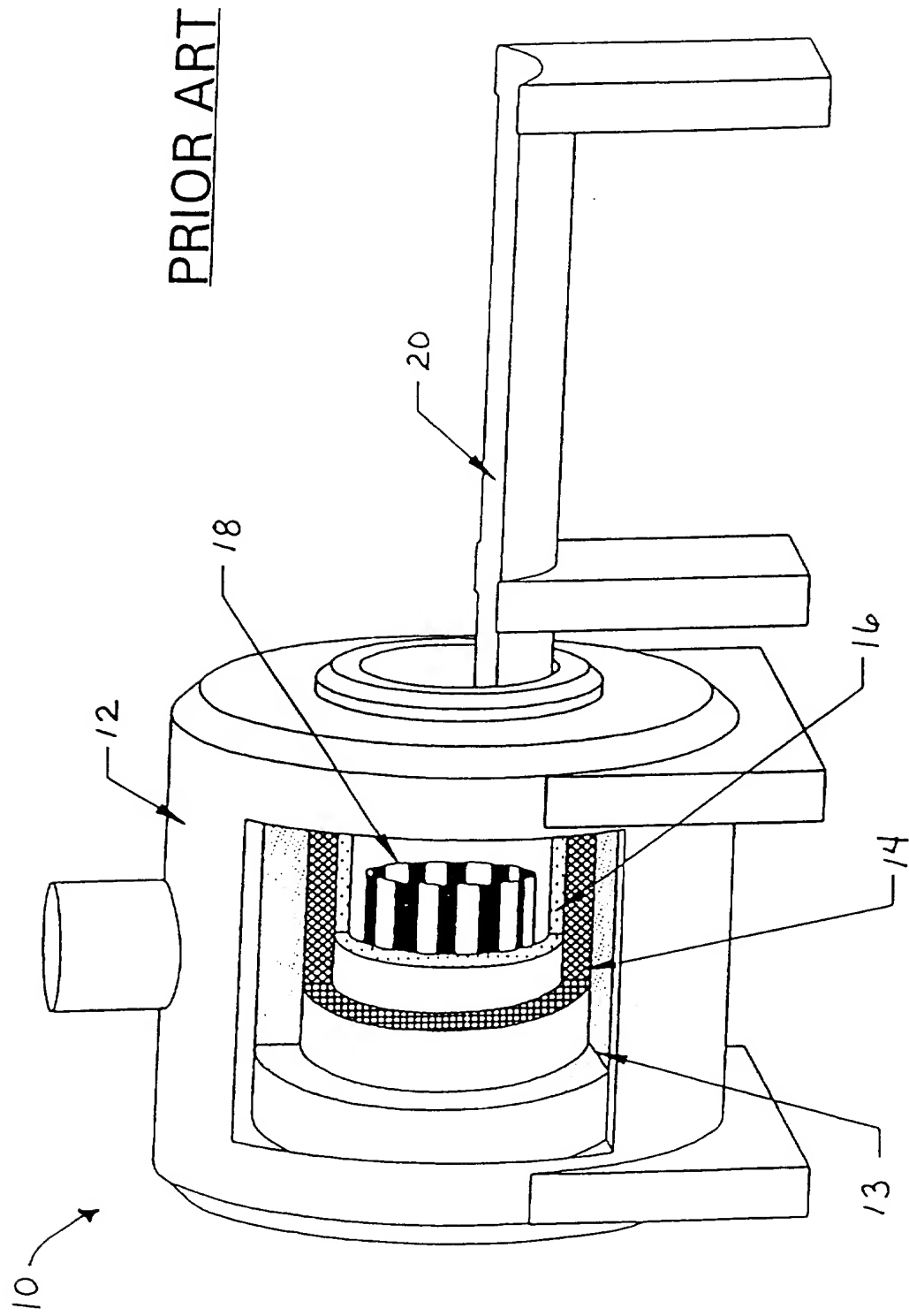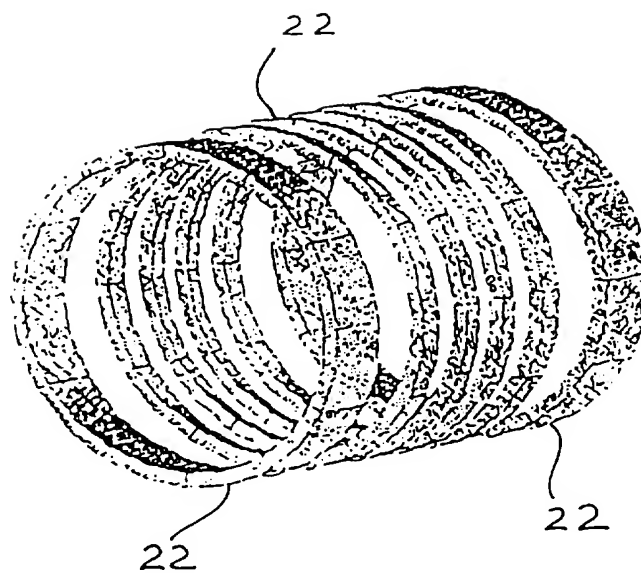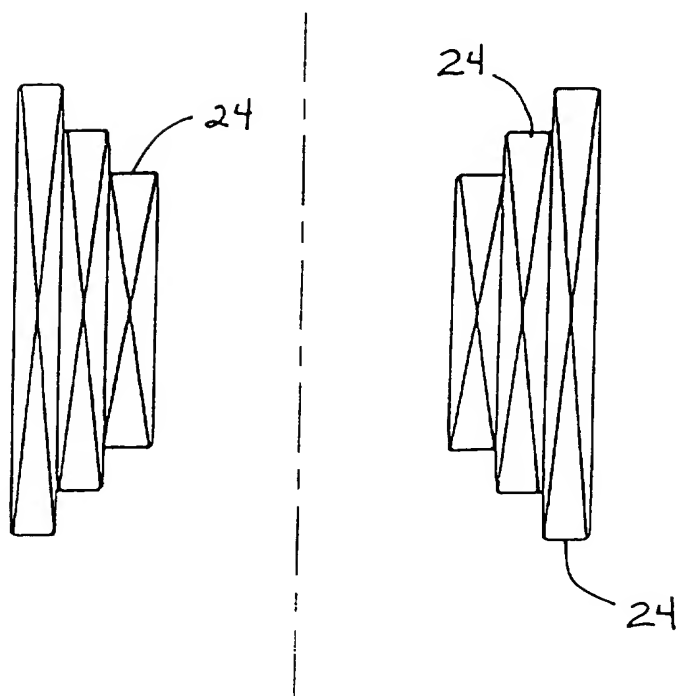

FIG. 7

GB 2 308 451 A

PRIOR ART

FIG. 1

22

22

22

PRIOR ART

FIG. 2A

24

24

24

PRIOR ART

FIG. 2B

INPUT DATA
  – SHIM OR MAGNET DESIGN?
  – ORIENTATION
    – INITIAL VALUES OF
      PERTURBATION
      PARAMETERS & CONSTRAINTS

26

  – CALCULATE FIELDS
  – CALCULATE HARMONICS
    – CALCULATE SHIELDING

28

CHOOSE
ANNEALING
SCHEDULE AND PARAMETERS

30

ANNEAL
  SYSTEM
    UNTIL
      FROZEN

32

OUTPUT
  – WIRE POSITIONS
  – FINAL HARMONICS
     AND SHIELDING VALUES

34

Figure 3

36 — INITIALIZE STRUCTURE

38 — RE-ARRANGE STRUCTURE

40 — CALCULATE FIELD HARMONICS/ SHIELDING & WEIGHTED ERROR

42 — IS ERROR < SMALLEST ERROR?

NO

44 — METROPOLIS ALGORITHM

NO

YES

46 — RE-ARRANGED STRUCTURE NOW BECOMES THE BEST SO FAR

48 — IS No. OF SUCCESSES ENOUGH ?

50 — IS No. OF TRIES ENOUGH ?

NO

NO

YES

52 — -DECREASE TEMPERATURE -ADAPT STEP SIZE

54 — TRY TEMPERATURE RESTART?

YES

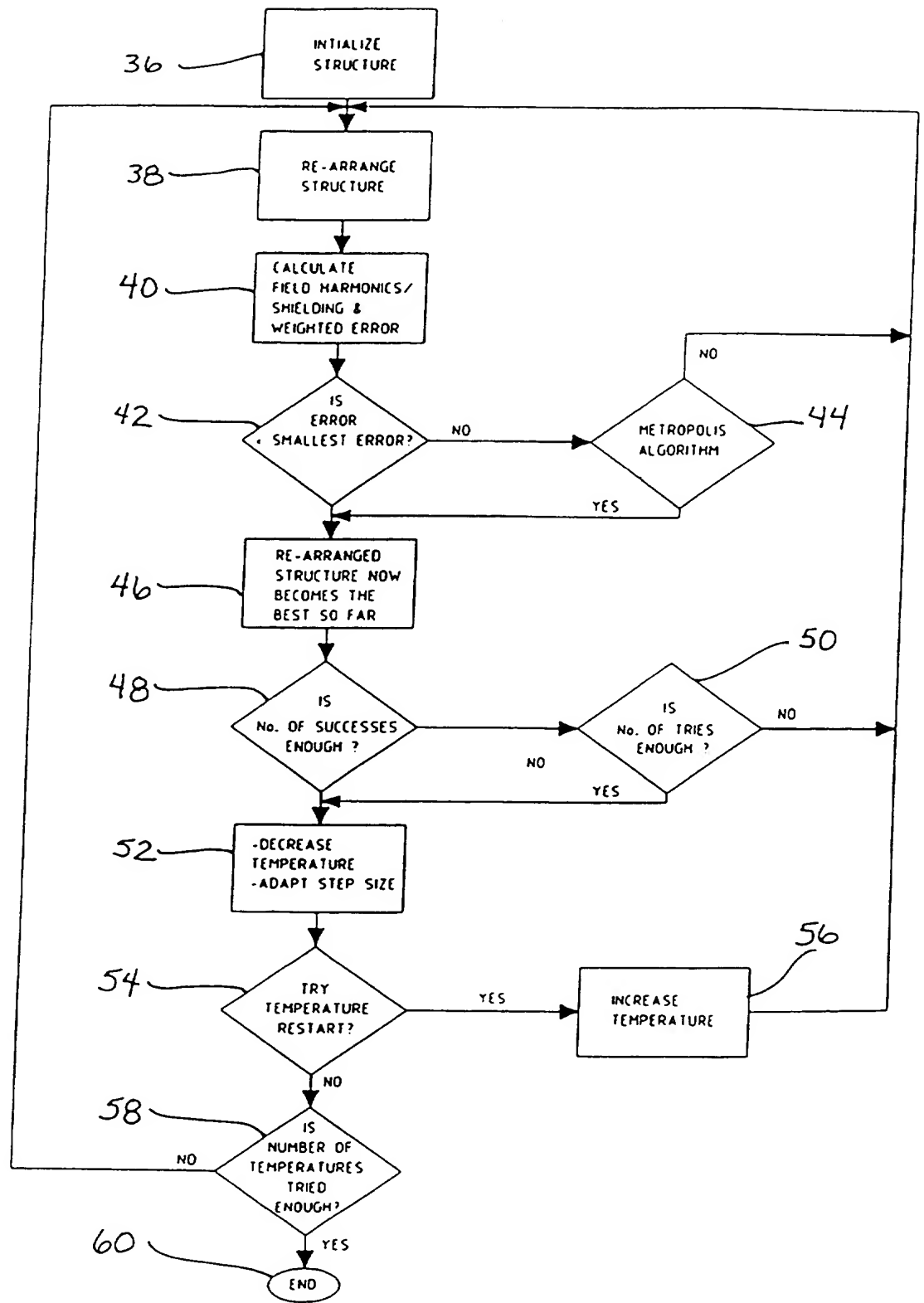56 — INCREASE TEMPERATURE

NO

58 — IS NUMBER OF TEMPERATURES TRIED ENOUGH?

NO

YES

60 — END

FIG. 4

FIG. 5

FIG. 6

FIG. 7

62

64

65

66

67

70

72

74
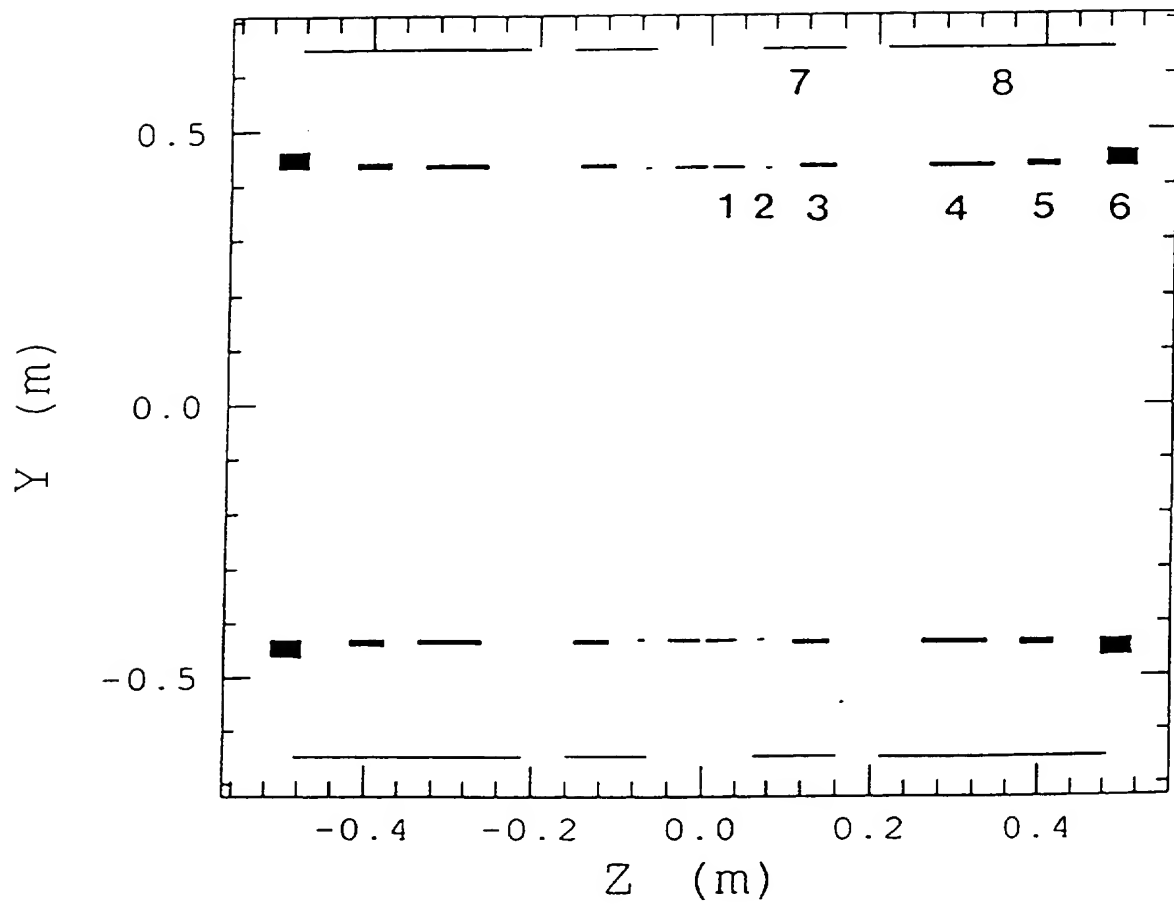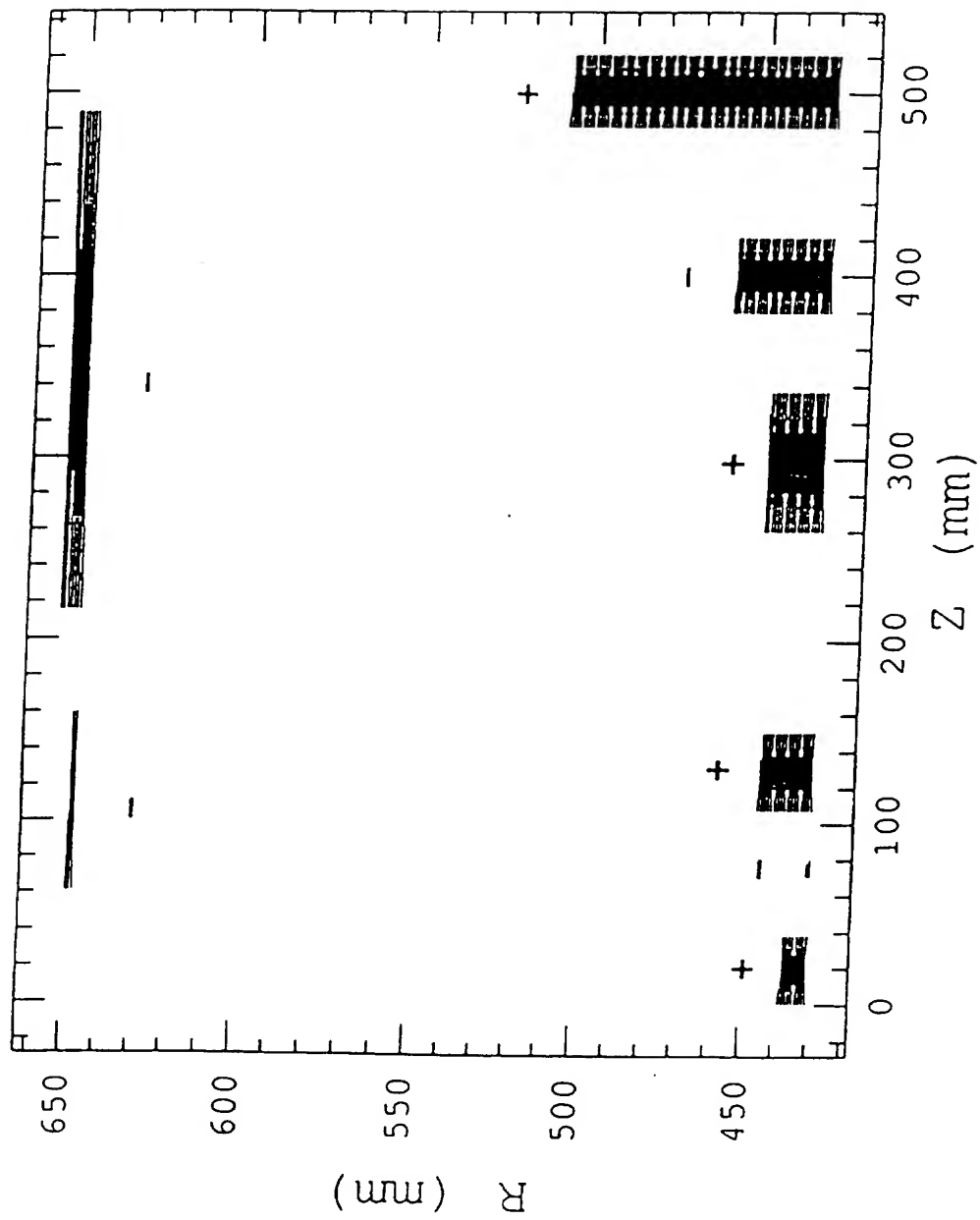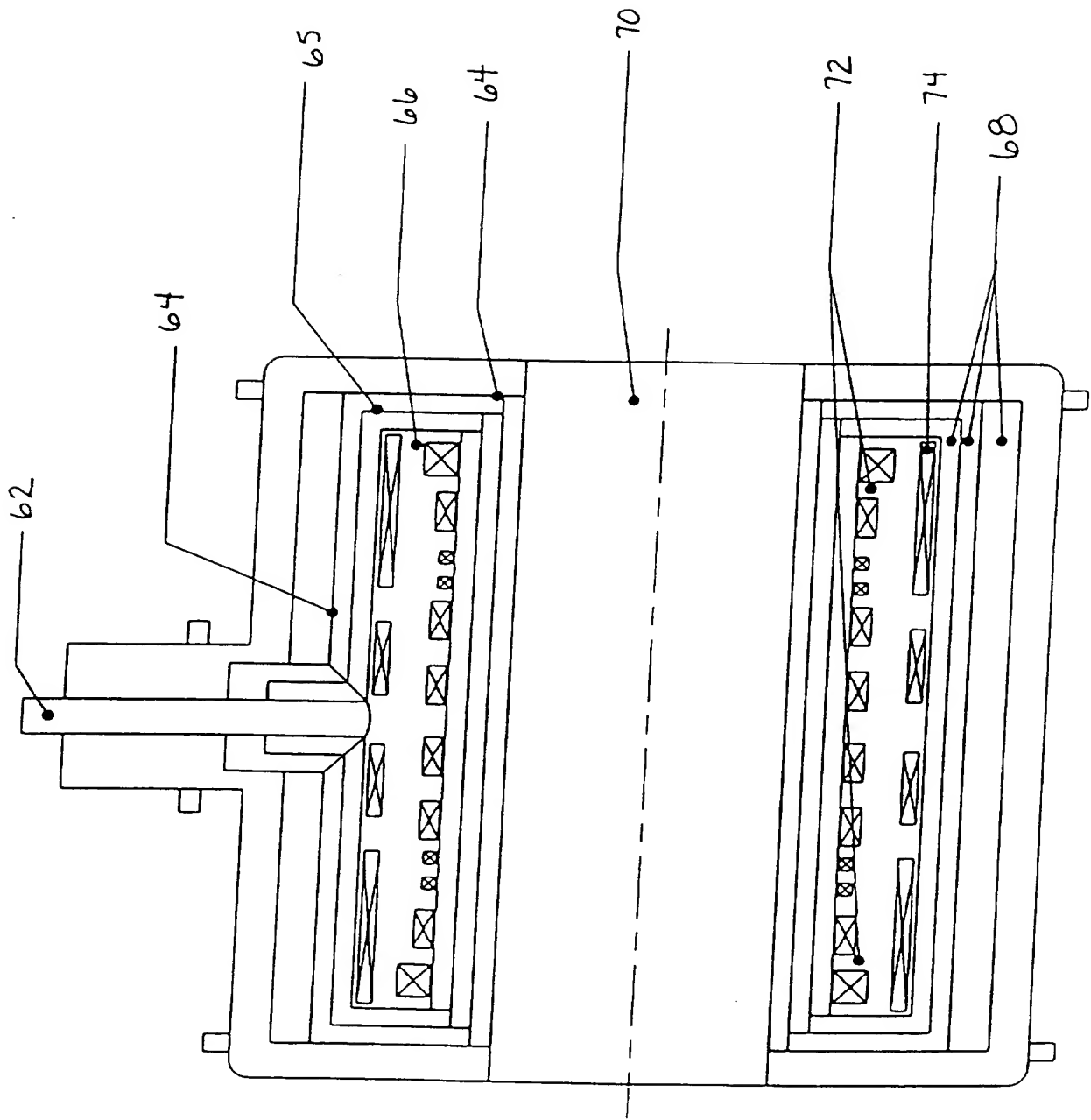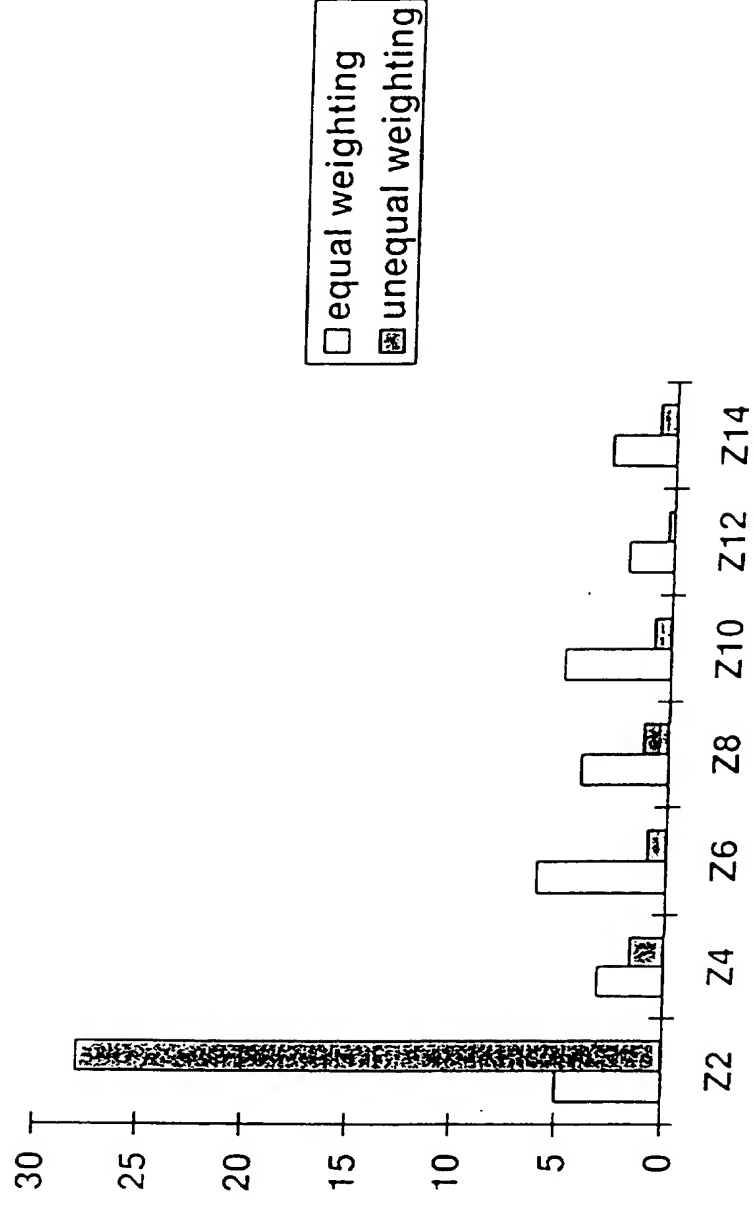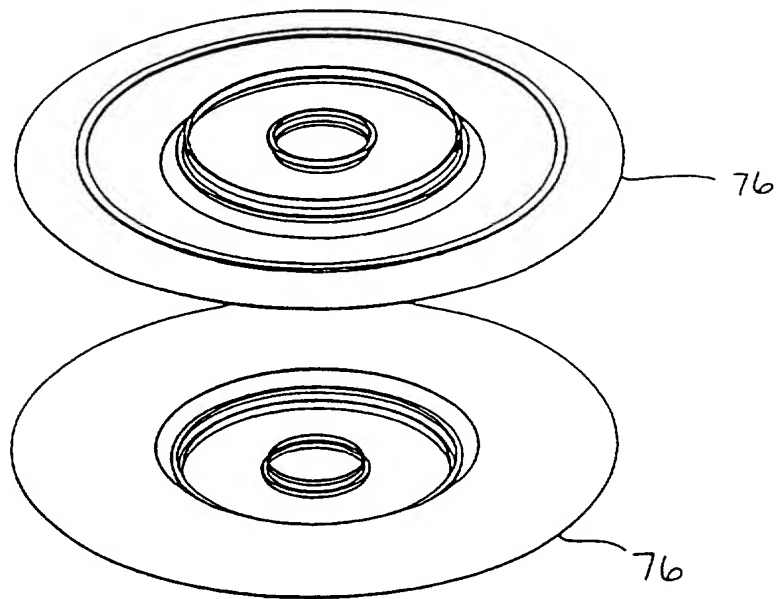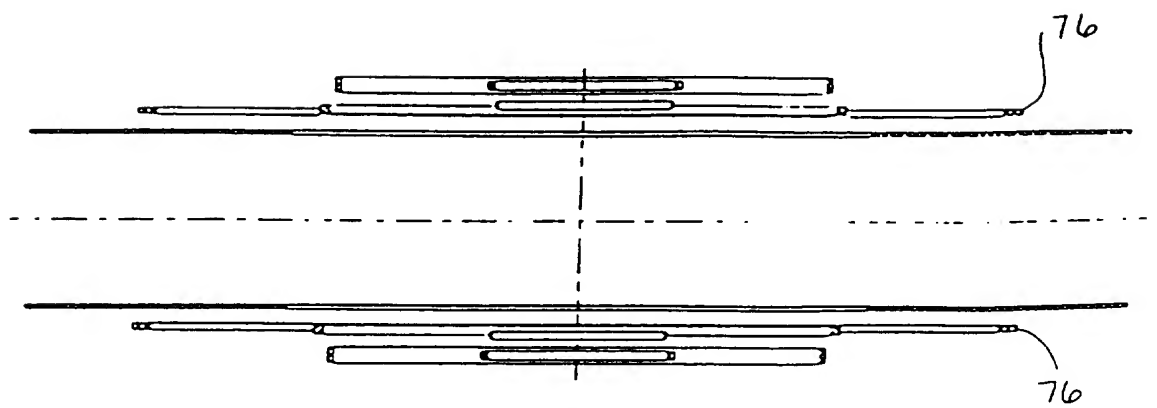
68

FIG. 8

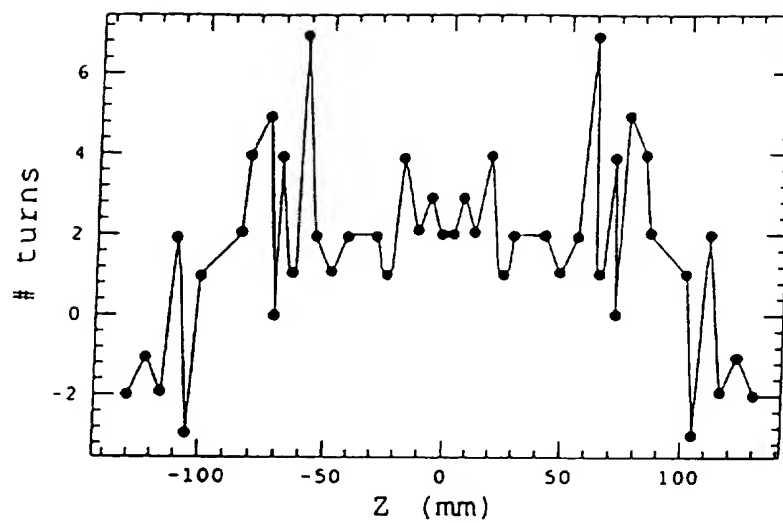Effect of Adjusting Weights in Error Function

FIG. 9

FIG. 10A

FIG. 10B

FIG. 11A
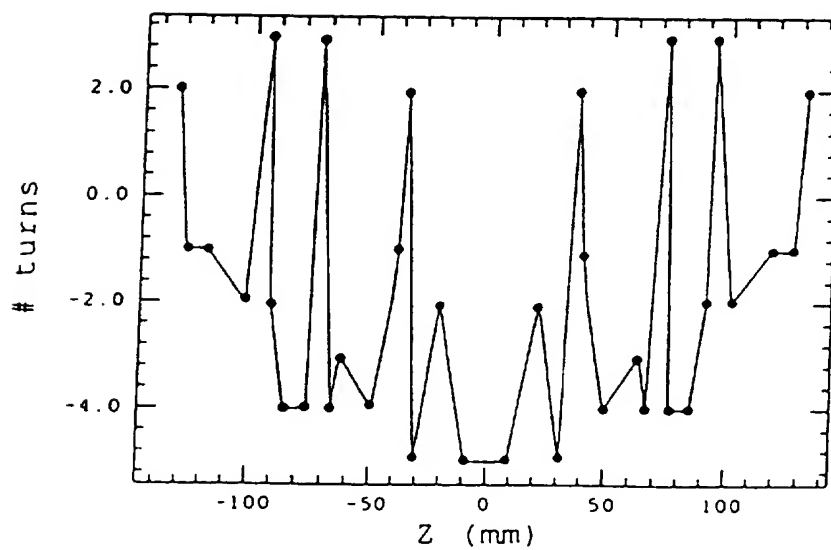
FIG. 11B
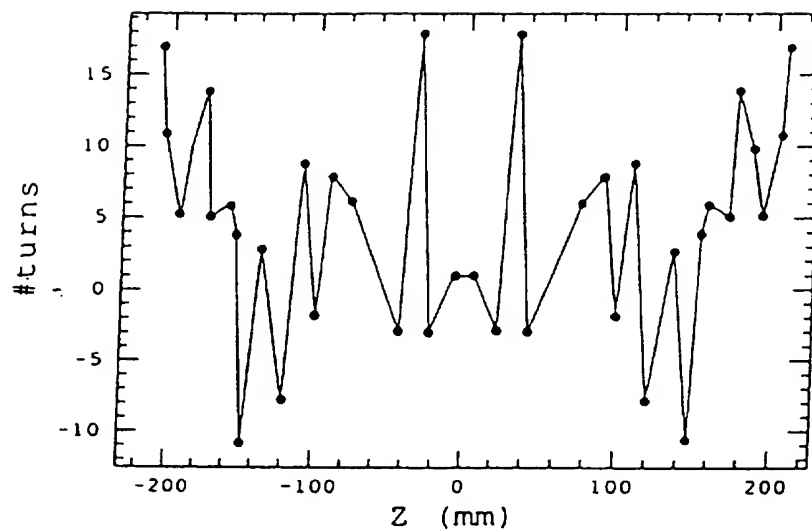
FIG. 11C
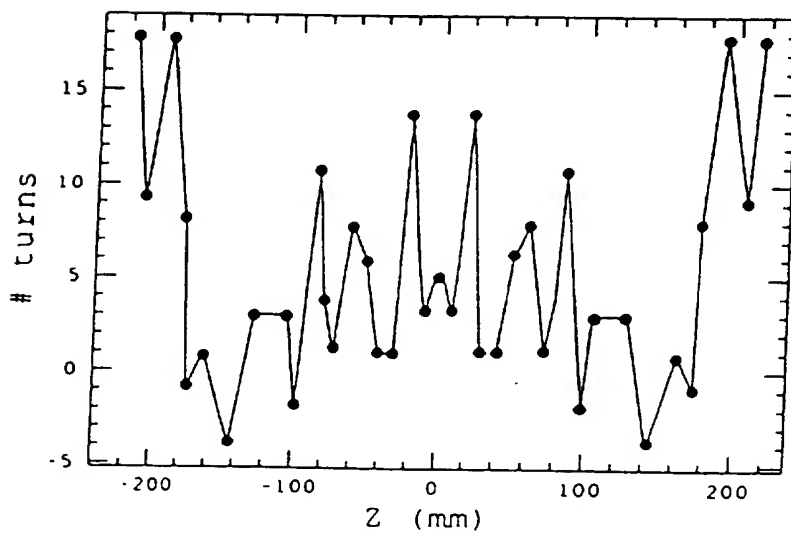
FIG. 11D
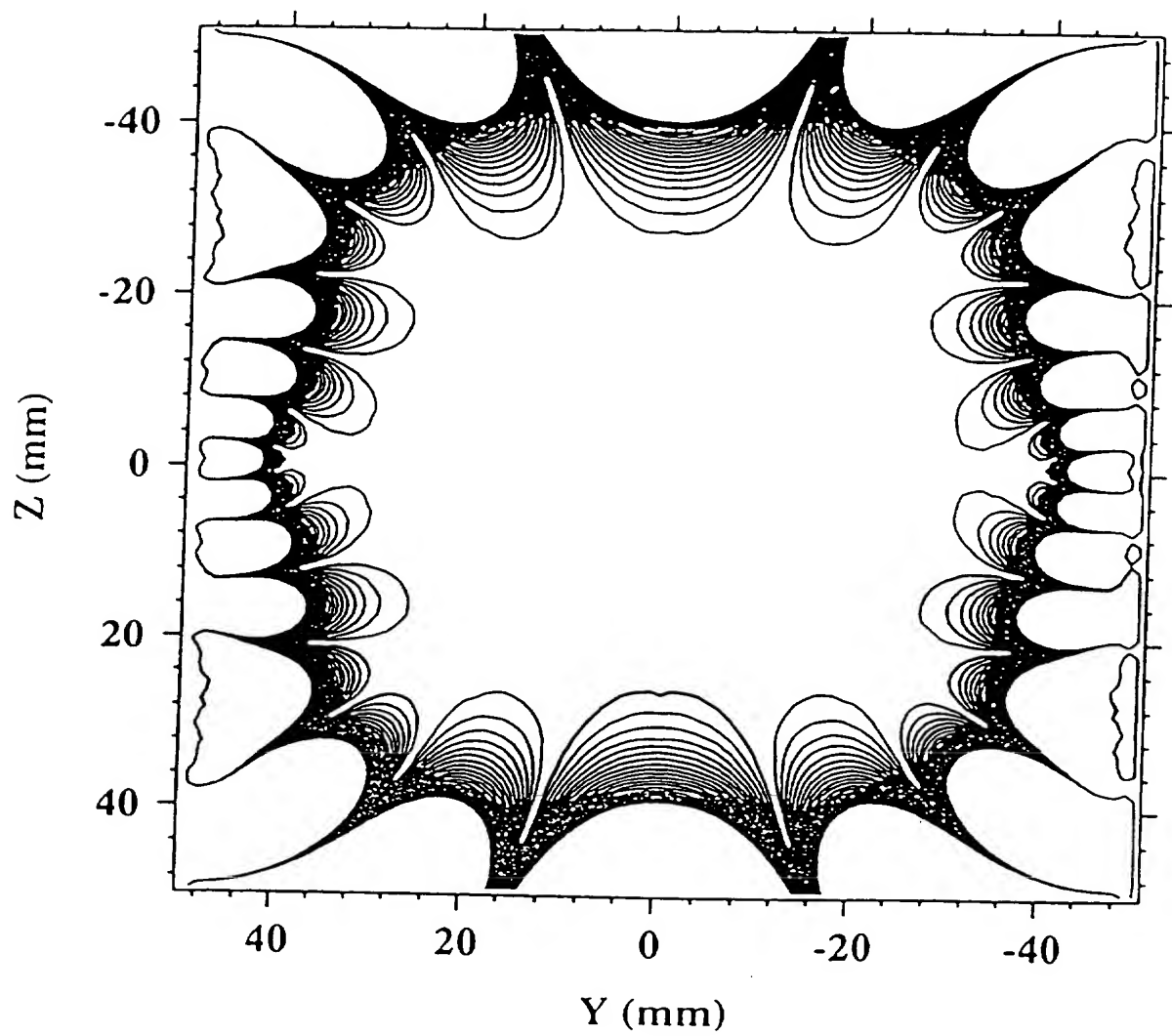
FIG. 12
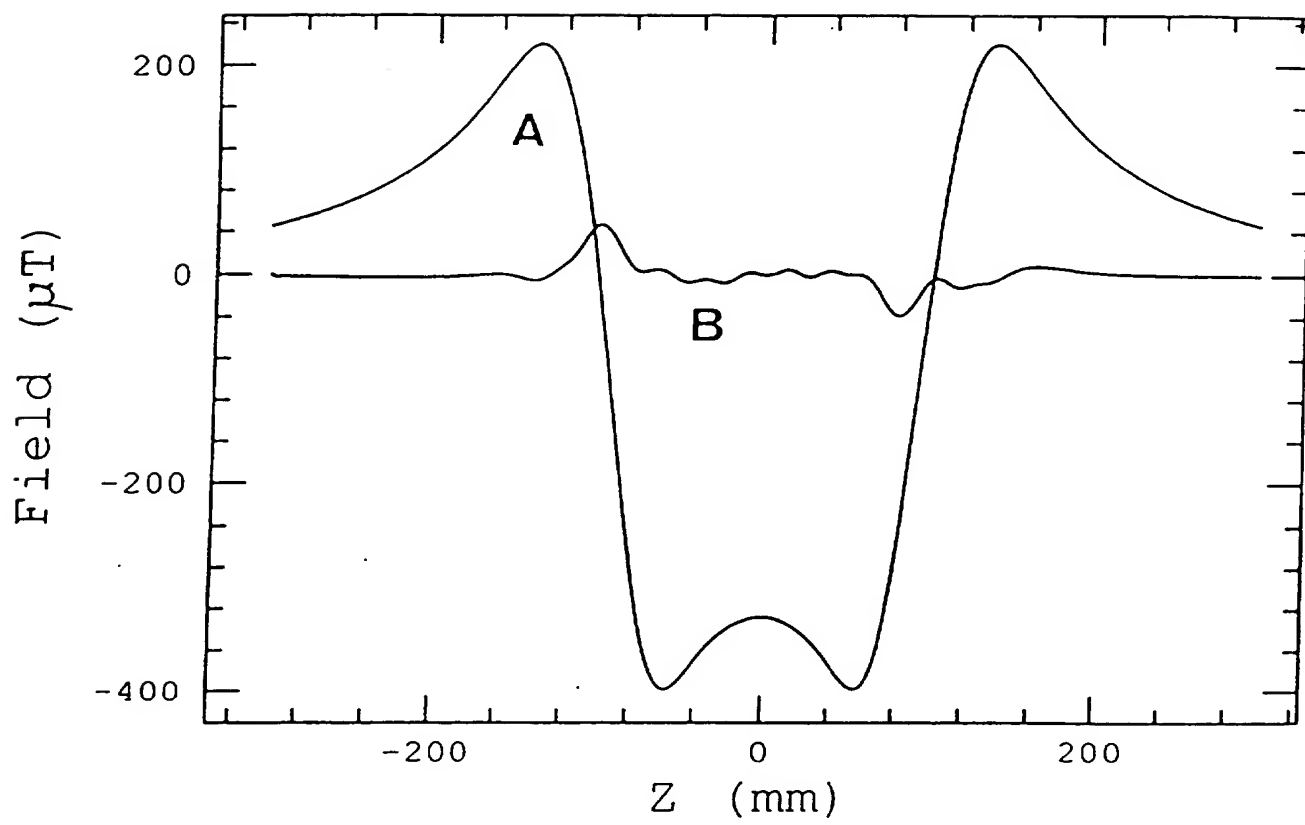
FIG. 13
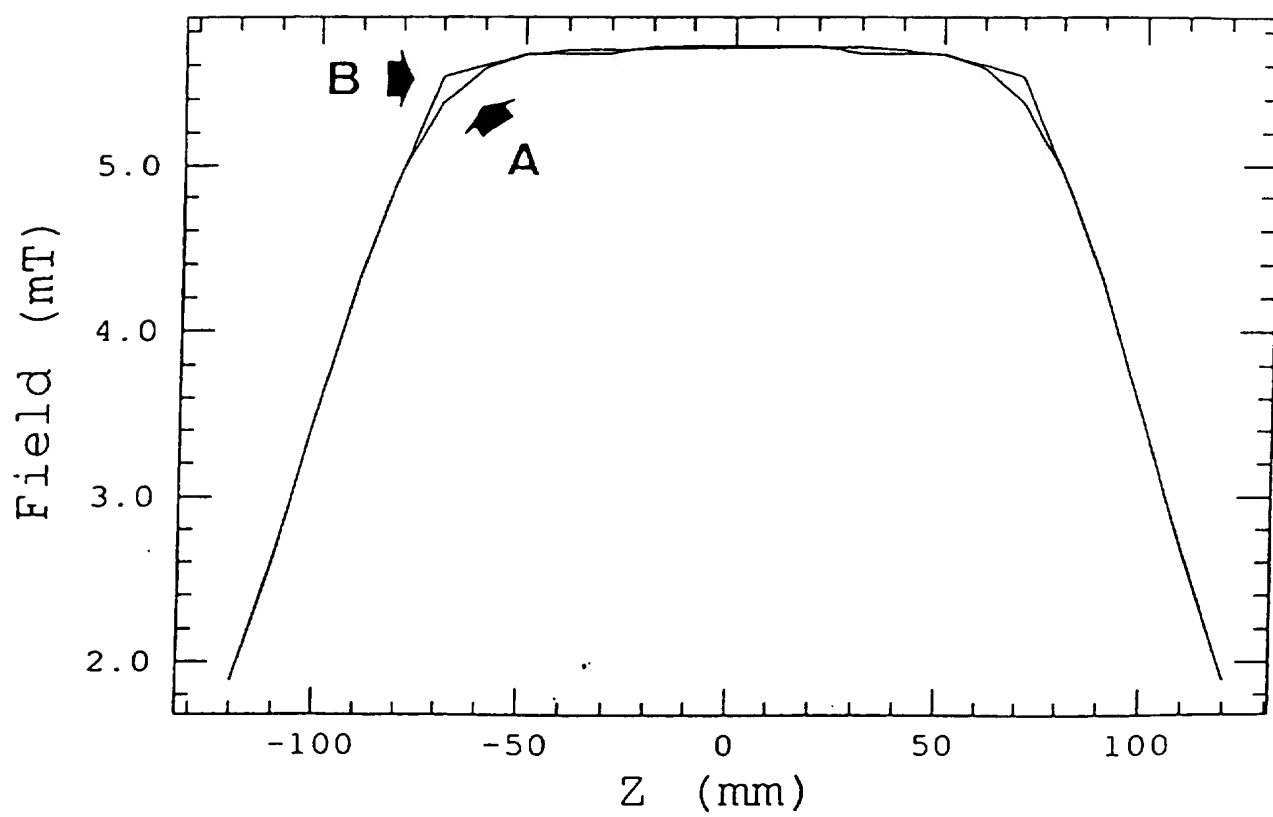
FIG. 14
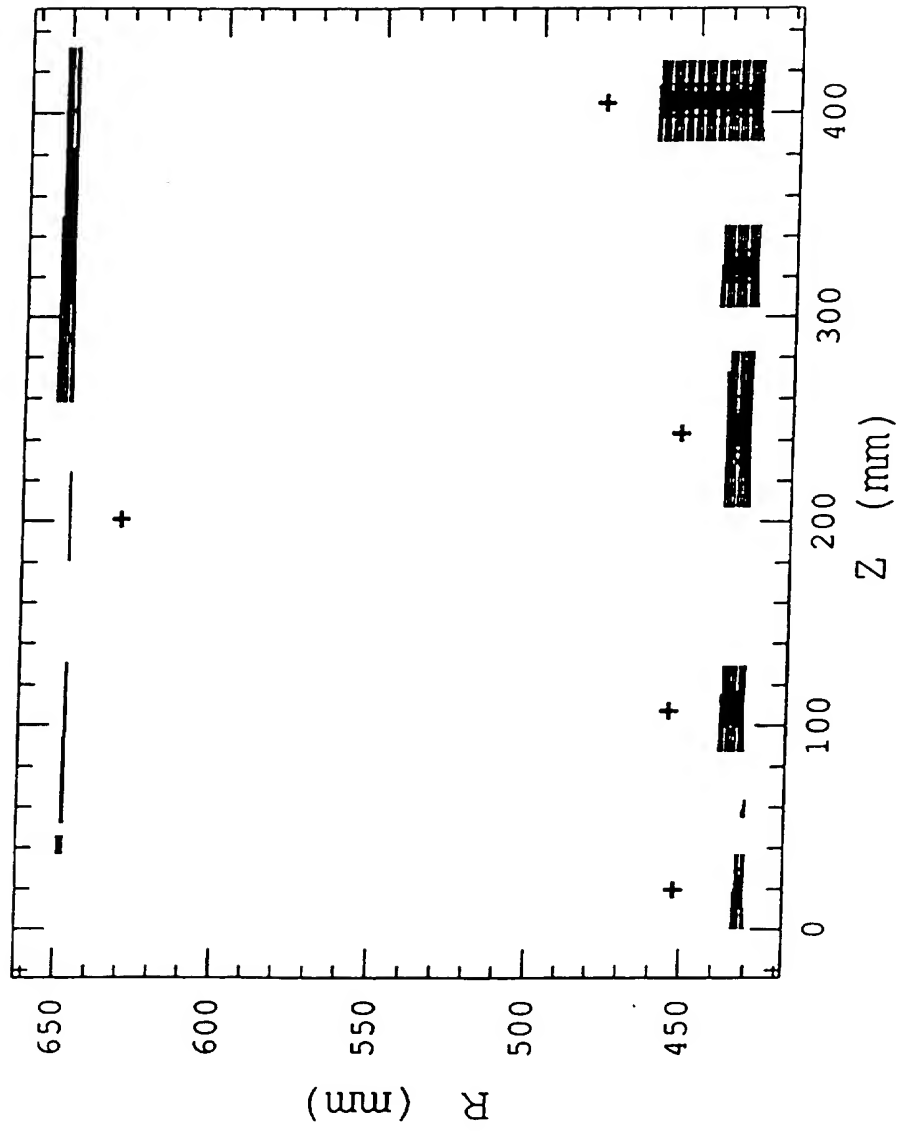
FIG. 15

MAGNETS FOR MAGNETIC RESONANCE SYSTEMS

FIELD OF THE INVENTION

This invention relates to magnets for magnetic resonance systems and to methods for designing and producing such magnets.

BACKGROUND OF THE INVENTION

Magnetic resonance systems are used in the medical field to produce diagnostic anatomical images and in various scientific and technological fields to study the structures of materials and the molecules therein.

When used to produce images, such systems are typically referred to as MRI systems (magnetic resonance imaging systems), and when used to study the spectra produced by specific nuclei, they are referred to as MRS systems (magnetic resonance spectroscopy systems) or high resolution systems. For ease of reference, the abbreviation "NMR" will be used herein to refer collectively to MRI, MRS, and high resolution systems, as well as to other magnetic resonance systems now known or subsequently developed. Discussions of NMR, including magnet systems for use in conducting NMR studies, can be found in, for example, Laukien et al., "Superconducting

NMR Magnet Design," Concepts in Magnetic Resonance, 6, 255-273, 1994; and Mansfield et al., NMR in Imaging and Biomedicine, Academic Press, Orlando, Florida, 1982. See also Golay, U.S. Patent No. 3,569,823; Briguet et al.,

5 U.S. Patent No. 4,833,410; Fujita, U.S. Patent No. 4,890,082; Hillenbrand et al., U.S. Patent No. 4,949,043; Aubert, U.S. Patent No. 5,014,032; Dorri et al., U.S. Patent No. 5,045,794; Kasten et al., U.S. Patent No. 5,276,399; Doddrell et al. U.S. Patent No. 5,289,127;

10 Laskaris et al., U.S. Patent No. 5,304,934; Laskaris et al, U.S. Patent No. 5,410,287; Dorri et al., U.S. Patent No. 5,416,415; Dorri et al., U.S. Patent No. 5,428,292; Laskaris, U.S. Patent No. 5,448,214; and Iwaoka et al., U.K. Patent Application 2,167,190.

15 The basic components of a magnet system 10 useful for performing magnetic resonance investigations are shown in Figure 1. The system of this figure is suitable for producing diagnostic images for human studies, similar systems being used for other applications.

20 System 10 includes magnet housing 12, superconducting magnet 13, shim coils (also referred to herein collectively as the "shim magnet") 14, gradient coils (also referred to herein collectively as the "gradient magnet") 16, RF coils 18, and patient table 20. As is

25 well known in the art, magnet 13 serves to produce a

substantially uniform field (the B_0 field) in the region
of the system where the nuclear magnetic resonance signal
will be generated (referred to herein as the "homogeneous
region").

5   Preferably, the uniformity of the field produced by
magnet 13 is on the order of about 20 ppm or less prior to
shimming for a homogeneous region having a volume of at
least about 40 x 10^3 cubic centimeters.   Shim coils 14
serve to reduce the variation in B_0 within the homogeneous
10   region to even lower levels. See, for example, Golay, U.S.
Patent No. 3,569,823.

RF coils 18 are used to generate the NMR signal by
irradiation of the particular nuclei under study at the
Larmor frequency for those nuclei, e.g., about 100
15   megahertz for ^1H at a B_0 of 2.35 Tesla.   The RF coils may
also be used to receive the NMR signal when generated or
separate coils can be used for this purpose if desired.
Gradient coils 16 serve to spatially encode the NMR
signal, thereby allowing the formation of a multi-
20   dimensional representation of the NMR-responsive parameter
under study.

Conventional superconducting magnet systems used for
NMR can be broadly classified as being of the horizontal
or the vertical type, with the horizontal type being more
25   commonly used for MRI applications and the vertical type

for MRS or high resolution applications. Vertical systems are generally constructed from co-cylindrical, multi-winding solenoids of varying lengths, while horizontal magnets are generally constructed of multi-winding coils

5   distributed along the longitudinal axis of the magnet.

Figures 2A and 2B show typical constructions for conventional horizontal and vertical superconducting magnets. The multi-winding primary coils are identified by the reference number 22 in Figure 2A; the multi-winding

10   primary solenoids are identified by the reference number 24 in Figure 2B. As discussed below, the present invention can be used with both types of magnets.

In modern medical imaging there is a distinct and long-felt need for magnet systems which have a shorter

15   overall length. The typical patient aperture of a conventional MRI machine is a cylindrical space having a diameter of about 0.6-0.8 meters, i.e., just large enough to accept the patient's shoulders, and a length of about 2.0 meters or more. The patient's head and upper torso

20   are normally located near the center of the patient aperture, which means that they are typically about a meter from the end of the magnet system.

Not surprisingly, many patients suffer from claustrophobia when placed in such a space. Also, the

25   distance of the patient's head and torso from the end of

the magnet system means that physicians cannot easily assist or personally monitor the patient during a MRI procedure, which can last as long as an hour or two.

In addition to its affects on the patient, the length of the magnet is a primary factor in determining the cost of a MRI machine, as well as the costs involved in the siting of such a machine. In order to be safely used, MRI machines, as well as MRS and high resolution machines, often need to be shielded so that the magnetic fields surrounding the machine at the location of the operator are below FDA specified exposure levels. By means of shielding, the operator can be safely sited much closer to the magnet than in an unshielded system. Longer magnets require more internal shielding and larger shielded rooms for such safe usage, thus leading to higher costs.

The critical problem in trying to make the magnet of a NMR machine shorter (e.g., to make the overall length less than about 1.5 meters) is keeping B_0 uniform (e.g., keeping the variation in B_0 less than about 20 ppm before any shimming of the basic field produced by the primary magnet) over a large homogeneous region (e.g., a region having a volume of at least about 40×10^3 cm^3). (Note that the diameter of a sphere having a volume of 40×10^3 cm^3 is about 42 cm, which is larger than the regions of the body which normally are imaged, e.g., the head, which

has a width of about 20 cm, and the chest cavity, which has a width of about 35 cm.)   Prior to the present invention, this combination of a short overall length and a large homogeneous region has not been achievable.

5   The most commonly used approach for designing conventional NMR magnet systems has involved expanding the longitudinal component of the magnetic field produced by the magnet in terms of Legendre polynomials, the normal basis set in spherical coordinates, and solving a set of

10   simultaneous equations in those polynomials. See Laukien et al., "Superconducting NMR Magnet Design," Concepts in Magnetic Resonance, 6, 255-273, 1994. The set of simultaneous equations relate the properties of the coils making up the magnet (e.g., the number of coils, the axial

15   locations of the coils, the number of windings in each coil, and the magnitude of the driving current in the system) to the overall longitudinal field produced by the magnet. The goal of the process is to null spherical harmonics above the lowest order in the homogeneous

20   region, while still producing a B_0 value (the lowest order harmonic) which is sufficiently high. Although this procedure has been effective in designing magnet systems having long overall lengths, the procedure has not been able to identify coil properties which will produce the

25   desired B_0 homogeneity for short magnets.

Recently, efforts have been made to apply the technique of simulated annealing to the problem of magnet design. See Crozier S and Doddrell D M 1993 Gradient Coil Design by Simulated Annealing *J. Magn. Reson.* **103** 354-57;

5 Crozier S, Forbes L K and Doddrell D M 1994a The design of short transverse Gradient coils by Simulated Annealing *J. Magn. Reson.* **10** 126-28; Crozier S, Dodd S and Doddrell D M 1994b The Design of Shielded Quadrupolar Gradient Coils for MRI by Simulated Annealing *IEEE Trans. Magn.* **30**

10 1242-46; Simkin J and Trowbridge C W 1992 Optimizing electromagnetic devices combining direct search methods with simulated annealing *IEEE Trans. Magn.* **28** 1545-48.

Simulated annealing is a stochastic optimization process in which selected parameters of a system are

15 optimized by minimizing an error function by making small random perturbations in the selected system parameters and using a methodology based on Boltzmann statistics to determine whether or not a particular perturbation is "accepted" for use in the optimization of the system. In

20 addition to perturbing the parameters, the process can also include constraints on one or more of the parameters.

The critical aspects of any simulated annealing process include: 1) the selection of the parameters, 2) the selection of any constraints on the parameters, and 3)

25 the choice of the error function. In the case of magnet

design, the selected parameters prior to the present invention have been the axial locations of the coils, the number of windings in each coil, and the magnitude of the driving current passing through the system.

5   Significantly, prior art simulated annealing procedures have not used the number of coils, the radial sizes of the coils or the winding direction (i.e., the direction of current flow in individual coils) as perturbation parameters. Similarly, the prior art has not

10   applied constraints to the simulated annealing procedure and, in particular, have not constrained the overall length of the magnet.

The error functions used in the prior art have also limited the effectiveness of the simulated annealing

15   technique. In particular, the error function used in Crozier et al. (1993) to design longitudinal gradient coils was a combination of an inductive term, a power term, a sum of field gradients in a longitudinal cross-sectional plane, and, optionally, a longitudinal shielding

20   term. The same error function was used in Crozier et al. (1994a) and Crozier et al. (1994b) in the design of transverse gradient coils and quadrupolar gradient coils, respectively. This error function is deficient because it cannot distinguish between the different harmonic

25   components which make up the overall magnet field and thus

its sensitivity to the perturbations of the simulated annealing process is less than optimal. Moreover, this error function cannot be used to design superconducting magnet 13 since it makes the gradient of the field uniform as opposed to making B_0 uniform.

The error function used in Simkin et al. was a unweighted sum of field harmonics. The failure to included weighting coefficients in this error function severally limits the usefulness of the Simkin et al. approach. In accordance with the present invention, it has been determined that it is the relative contributions of the various spherical harmonics making up the overall field which are critical in the design of a magnet using simulated annealing. See Example 2 below. Such relative weighting is impossible with the Simkin et al. error function. Furthermore, Simkin et al. provide no mechanism for designing shielded magnets, such shielding being essential for practical NMR systems which satisfy FDA regulations.

SUMMARY OF THE INVENTION

In view of the foregoing, it is an object of the present invention to provide improved methods for designing magnets for magnetic resonance systems, including, in particular, but without limitation, superconducting magnets, gradient magnets, and shim

magnets. It is a specific object of the invention to provide improved simulated annealing procedures for the design of such magnets.

It is a further object of the invention to provide superconducting magnets which have a short length and yet a large homogeneous region.

It is another object of the invention to provide superconducting magnets where the sample to be studied, e.g., all or part of the human body, can be introduced into the homogenous region through an aperture whose orientation is not along the longitudinal axis of the superconducting magnet.

It is an additional object of the invention to provide superconducting magnets of the foregoing types which have low external (stray) fields.

It is a further object of the invention to provide shielded and unshielded shim and gradient magnets which have a short length and yet generate a spherical harmonic field component which is substantially pure. Again, with respect to these magnets, it is an object of the invention to provide designs which produce low external (stray) fields.

To achieve these and other objects, the invention provides a simulated annealing procedure for designing a magnet in which the number of coils, the radial sizes of

the coils, and the direction of current flow in the coils are used as optimization parameters and the overall length of the magnet is used as a constraint. Further, the procedure uses an error function which includes a weighted sum of spherical harmonic components and which may include longitudinal and transverse shielding terms.

By means of this design procedure entirely new superconducting magnet designs not before available in the art have been achieved. In particular, superconducting magnets having primary coils with opposing current flows have been designed. These designs preferably employ a relatively large number of coils, e.g., more than the standard value of six coils used in essentially all currently available whole body MRI machines. Also, the designs may employ primary coils of varying radii.

In certain of these designs, the primary coils have a biplanar arrangement which allows the sample, e.g., the patient, to be introduced into the homogeneous region along an axis orthogonal to the longitudinal axis of the coils.

Improved shielding magnets are also provided by the improved magnet design procedures of the invention. As with the primary coils, the design procedure has led to shielding coils having opposed current flows, as well as

to shielding magnets having relatively large numbers of shielding coils, e.g., more than four shielding coils.

In accordance with the preferred embodiments of the invention, magnets for magnetic resonance systems are designed which have a length to diameter ratio of less than 1.5 and most preferably less than 1.2. In particular, superconducting magnets are provided which have a short overall length, e.g., less than about 1.5 meters and preferably less than about 1.2 meters, and a substantially uniform B_0 field, e.g., less than about 20 ppm before any shimming is performed, for a large homogeneous region, e.g., a region whose volume is at least about 40×10^3 cm^3 and preferably at least about 45×10^3 cm^3. When shielded, these superconducting magnets also have low external (stray) fields.

When applied to the design of shim and gradient magnets, the magnet design procedures of the invention have led to the development of magnets having high purity, short length, and low external (stray) fields.

In accordance with other aspects of the invention, the general structure of the novel magnet designs achieved using the improved simulated annealing procedures of the invention is used as the starting point for other processes for designing magnets, such as the simultaneous equations approach discussed above. For example, in

accordance with these aspects of the invention, the design process can begin by specifying that the magnet must have at least six coils and at least one coil wherein the current is in an opposite direction to the current in at least one other coil. With this as the starting point, procedures other than simulated annealing are able to achieve magnet designs which they otherwise could not achieve.

The specifics of the magnet design procedures of the invention and examples of the various magnet configurations developed using these procedures are presented below in connection with the discussion of the preferred embodiments of the invention.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a schematic diagram of a prior art MRI machine.

Figures 2A and 2B are schematic diagrams of prior art horizontal and vertical primary coils for an NMR machine.

Figure 3 is a general flow chart for the simulated annealing procedure of the invention.

Figure 4 is a more detailed flow chart for the simulated annealing procedure of the invention.

Figure 5 is a plot of a typical error function versus number of iterations for the simulated annealing procedure of the invention.

Figure 6 is a cross-sectional, schematic diagram of a shielded superconducting magnet designed in accordance with the present invention.

Figure 7 is an expanded scale view of the upper right hand quadrant of Figure 6.

Figure 8 is a schematic cross-sectional view through a MRI machine designed in accordance with the present invention.

Figure 9 is a comparative plot of relative strength versus spherical harmonic for a magnet designed using weighted spherical harmonics (darker hatching) and one designed using unweighted spherical harmonics (lighter hatching).

Figures 10A and 10B are perspective and cross-sectional view of a biplanar magnet designed in accordance with the invention.

Figure 11A-11D show exemplary configurations for various shim magnets designed in accordance with the invention.

Figure 12 is a contour plot for a Z0 shim magnet designed in accordance with the invention.

Figure 13 is a plot of external field strength versus longitudinal axial dimension for a Z0 shim magnet designed in accordance with the invention.

Figure 14 is a comparative plot showing theoretical (curve A) and experimental (curve B) field strengths along the longitudinal axis of a Z0 shim magnet designed in accordance with the invention.

Figure 15 is a cross-sectional, schematic diagram of the upper right hand quadrant of a shielded superconducting magnet designed in accordance with the present invention.

The foregoing drawings, which are incorporated in and constitute part of the specification, illustrate the preferred embodiments of the invention, and together with the description, serve to explain the principles of the invention. It is to be understood, of course, that both the drawings and the description are explanatory only and are not restrictive of the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

As discussed above, the method aspects of the present invention relate to the use of an improved simulated annealing procedure to design magnets for magnetic resonance systems. A general flow chart for the procedure is shown in Figure 3 and a more detailed flow chart is shown in Figure 4.

As shown in Figure 3, in the first step of the process (box 26), data is inputted to a computer system regarding: (1) the type of magnet which is to be

designed, e.g., a superconducting magnet, a shim magnet, or a gradient magnet; (2) the orientation of the magnet, e.g., whether the longitudinal axis of the magnet is to lie in a horizontal or vertical plane with a horizontal

5   orientation generally meaning that the coils of the magnet will be located at discrete locations along the magnet's longitudinal axis and a vertical orientation generally meaning that the coils of the magnet will be in the form of nested solenoids; (3) an initial guess at the

10   parameters which will be perturbed during the simulated annealing process, e.g., the number of coils, the positions of the coils, the number of windings per coil, and the direction of current for each coil; and (4) the constraints on the system, e.g., the length of the magnet,

15   the maximum current in the system, the desired value of B_0, and the desired location of the "5 gauss contour line" for shielded magnets. Although not explicitly shown in box 26, the inputted data will also normally include the configuration of the sample (e.g., patient) aperture

20   (e.g., its dimensions and shape) and whether the magnet is to be shielded or not, as well as information regarding the minimum inter-coil spacing, the maximum number of windings per coil, wire thicknesses, and similar information depending on the particular magnet being

25   designed.

With regard to the direction of current for each coil, it should be noted that in a typical superconducting magnet the coils are arranged in series. Accordingly, the direction of flow of current in a coil is determined by the direction in which the coil is wound around the longitudinal axis, as opposed to being determined by the polarity of the feed to each coil. Similarly, in a typical arrangement, the majority of shielding coils are wound in a direction opposite to the direction of winding of the majority of primary coils.

The data input can be performed using any of the standard techniques known in the art for inputting data to a computer system, including, keyboard entry, magnetic medium entry, optical medium entry, and the like.

In the second step of the overall process (box 28 in Figure 3; see also box 36 of Figure 4), the initial guess is used to calculate the field at selected field points within and around the magnet. The field values outside the magnet are used to calculate the shielding terms in the simulated annealing error function (see below). The field values inside the magnet are used to calculate the spherical harmonic components of the internal field, and those components are then weighted and used in the simulated annealing error function (see below). The field points inside the magnet are typically selected to lie on

the outer boundary, e.g., spherical edge, of the homogeneous region.

The field values inside of the magnet are calculated using the well known Biot-Savart equation which relates the current in various winding segments to field values. (Note that in the typical case, the winding segments will be portions of a circle. However, if the sample aperture has a different shape, the segments are located on paths which correspond to that shape. These considerations, of course, apply to the calculation of both the internal and external fields.) Once the internal field values have been calculated, a spherical harmonic deconvolution is performed. Discussions of spherical harmonics and spherical harmonic deconvolutions can be found in, for example, T. M. MacRobert, Spherical Harmonics - An Elementary Treatise on Harmonic Functions with Applications, Metheun, London, 1927; and M. Abramowitz and I.A. Stegun, Handbook of Mathematical Functions, National Bureau of Standards, Dover Publications, Inc., New York, 1970.

As is known in the art, a spherical harmonic expansion of a magnetic field expresses the field as a sum of orthogonal terms. The most straightforward approach to obtaining a spherical harmonic expansion of a magnetic field is to determine the magnetic field at points on a

spherical surface (the edge of the homogeneous region) surrounding the centre (origin) of the magnet. It should be noted that the centre used for the spherical harmonic expansion need not be the geometric centre of the physical magnet if it is desired to produce a magnet having a "sweet spot" other than at the geometric centre.

Spherical harmonics take the form

$$B_{z_{nm}}(r,\theta,\phi) = r^n(a_{nm}\cos m\phi + b_{nm}\sin m\phi)\,P_{nm}(\cos\theta) \tag{1}$$

and are solutions of Laplace's equation $\nabla^2 B_z = 0$. In spherical coordinates, the field B_z can be represented by an expression of the form

$$B_z(r,\theta,\phi) = \sum_n \sum_m B_{z_{nm}}(r,\theta,\phi) \tag{2}$$

NMR is generally concerned with the field in the direction of the magnet axis (the z direction by convention). In equation (1), Bz_{nm} is the spherical harmonic of order n and degree m, a_{nm} and b_{nm} are constants, r is the radial distance from the magnet isocenter and $P_{nm}(\cos\theta)$ are the associated Legendre

functions. The spherical harmonic Bz_{nm} and the surface spherical harmonic T_{nm}, where

$$T_{nm} = (\cos m\phi + \sin m\phi)P_{nm}(\cos\theta) \tag{3}$$

5

have the property of being orthogonal when integrated over the surface of a sphere, i.e.,

10

$$\int_0^{2\pi}\int_{-1}^1 B_{z_{nm}}(u,\phi)\ T_{ij}(u,\phi)\ du\ d\phi\ =\ 0 \qquad n \neq i \text{ or } m \neq j$$

$$= r^n \frac{4\pi}{2n+1}\ a_{n0} \qquad n = i \text{ and } j = m = 0 \tag{4}$$

$$= r^n \frac{2\pi}{2n+1}\ \frac{(n+m)!}{(n-m)!}\ (a_{nm} + b_{nm})\ n = i \text{ and } m = j$$

15

where u = $\cos\theta$. This integral provides the means by which the spherical harmonic coefficients a_{nm} and b_{nm} can be determined for each spherical harmonic Bz_{nm}. In 20 particular, these coefficients can be determined from a field distribution by expanding the left-hand side of equation 4 by substituting equations 1 and 3 to give

$$\int_0^{2\pi} \int_{-1}^{1} B_z(u,\phi)\; T_{nm}(u,\phi)\, du\, d\phi$$

$$= \int_{-1}^{1} P_{nm}(u) \int_0^{2\pi} B_z(u,\phi)\; (\cos m\phi + \sin m\phi)\, d\phi\, du$$

(5)

Bz_{nm} having been replaced by the summation given in equation 2. $B_z(u,\phi)$ corresponds to points in the magnetic field which are measured on the surface of a sphere of

5   radius r (the homogeneous region). The inner integral on the right hand side of equation 5 is evaluated by Fourier transforming $B_z(u,\phi)$ with respect to ϕ for fixed u to give $F(u)$, while the outer integral is evaluated using Gaussian numerical integration. That is

10

$$\int P_{nm}(u)\, F(u)\, du \;\rightarrow\; \sum_u P_{nm}(u)\, W_u\, (F^c(u) + F^s(u))$$

(6)

where W_u are the Gauss weighting factors for each point u and the superscripts c and s refer to cosine and sine

15   Fourier transforms of the azimuthal data. The coefficients a_{nm} and b_{nm} can then be found by equating terms in expressions 4 and 6 to give:

$$b_{n0} = 0 \quad m = 0$$

$$a_{n0} = r^{-n} \frac{2n+1}{4\pi} \sum_u P_{n0}(u) \, W_u \, F^c(u) \quad m = 0$$

$$a_{nm} = r^{-n} \frac{2n+1}{2\pi} \frac{(n-m)!}{(n+m)!} \sum_u P_{nm}(u) \, W_u \, F^c(u) \quad m > 0$$

$$b_{nm} = r^{-n} \frac{2n+1}{2\pi} \frac{(n-m)!}{(n+m)!} \sum_u P_{nm}(u) \, W_u \, F^s(u) \quad m > 0$$

(7)

In the case of a superconducting magnet, e.g., magnet 13 in Figure 1, the field due to the magnet structure was calculated at 450 positions around the magnet centre at 12° azimuthal steps and on 15 longitudinal planes, allowing zonal and tesseral harmonics up to degree and order 14 to be calculated. The axial positions of the 15 planes were given by the radially scaled roots of the Legendre polynomial $P_{15}(\cos\theta)$. The field at these 450 points was calculated by Biot-Savart summations in which each winding was segmented into 100 pieces. The above analysis was then used to deduce the harmonics generated by each magnet configuration.

In the case of gradient and shim magnets, the field due to the magnet was calculated at 112 positions around the magnet centre at 22.5° azimuthal steps and on 7 longitudinal planes, allowing zonal and tesseral harmonics up to degree and order 6 to be calculated. Higher degrees and orders can, of course, be used if desired by

increasing the sampling of the homogeneous region. The axial positions of the 7 planes were given by the radially scaled roots of the Legendre polynomial $P_7(\cos\theta)$. The field at these 112 points was calculated by Biot-Savart

5   summations in which each winding was segmented into 100 pieces. Again, this analysis was then used to deduce the harmonics generated by each magnet configuration.

The full field and harmonic deconvolution for the superconducting magnets took on average about 2-3 minutes

10   to run on a Sun SPARCstation 10. The corresponding times for the shim and gradient magnets was about 0.5 minutes. Results of the harmonic deconvolution are typically listed by harmonic "name", a list of some of the more common of which appears in Table 1.

15   As also shown in box 28 of Figure 3, the initial guess is used to calculate the fields outside of the magnet to determine the level of shielding provided by any shielding magnets included in the overall magnet design. As with the internal fields, the field values outside of

20   the magnet are calculated using the Biot-Savart equation. Once calculated, a measure of the level of shielding (the "shielding measure") can be obtained by summing field values along one or more lines in the region of the magnet. For example, the level of longitudinal shielding

25   can be determined by summing the field levels along a line

parallel to the longitudinal axis and at a distance from that axis at which a 5 gauss field is desired. Similarly, the level of transverse shielding can be determined by summing the field levels along a line orthogonal to the longitudinal axis, again at a distance from the magnet where a 5 gauss field is desired. Either or both of these shielding measures can be used if desired. Similarly, other shielding measures can be used if desired.

At this point in the process, it may be desirable to consider whether the initial guess was reasonable. If the calculated harmonics and shielding measure(s) provide a reasonable starting point for the simulated annealing optimization, then the process proceeds to box 30 of Figure 3. If not, box 26 can be reexecuted with revised data until a reasonable starting point is obtained. A reasonable starting point, of course, will depend on the properties of the magnet which one desires and will be evident to persons skilled in the art from their knowledge of desirable magnet fields for NMR.

In box 30 of Figure 3, an annealing schedule and annealing parameters are selected. The considerations which are used in making this selection are discussed below in connection with Figure 4. Once the schedule and parameters are selected, the simulated annealing is performed until the system becomes "frozen" (box 32 of

Figure 3; see also the discussion of Figure 4 below). Finally, the result of the optimization is outputted in, for example, magnetic or hard copy form, e.g., graphical or tabular form. Alternatively, the output can be a display of the magnet's structure and the fields which the structure generates on, for example, a workstation monitor.

Using a Sun SPARCstation 10, the simulated annealing procedure can take about 2 hours for a shim or gradient magnet and about 1-2 days for a superconducting magnet.

Thereafter, the magnet can be manufactured using conventional NMR magnet construction techniques known in the art. See, for example, Laukien et al., "Superconducting NMR Magnet Design," Concepts in Magnetic Resonance, 6, 255-273, 1994; and Mansfield et al., NMR in Imaging and Biomedicine, Academic Press, Orlando, Florida, 1982.

Figure 4 illustrates a preferred procedure for performing the simulated annealing optimization. As discussed above, simulated annealing is a stochastic optimization method based on Boltzmann statistics that has the potential to find the global minimum of a defined error function in response to system perturbations. See Metropolis N, Rosenbluth A W, Rosenbluth M N and Teller A H 1953 Equations of state calculations by fast computing

machines *J. Chem. Phys.* **21** 1087-1092; and Kirkpatrick S, Gelatt C D and Vecchi M P 1983 Optimization by simulated annealing *Science* **220** 673-680.

In accordance with the invention, simulated annealing is performed by perturbing an array of coils randomly and independently along a constrained length (the magnet length) with the maximum number of windings at each position specified as well as the minimum inter-coil spacing to account for finite wire thickness. (See box 38 of Figure 4.) Current flow in individual coils can be positive or negative. The spherical harmonics for each perturbation are calculated as described above. (See box 40 of Figure 4.) The field outside a shielded magnet and its inductance may also be calculated.

A weighted sum of these factors then produces the error function (box 40 of Figure 4), a preferred form of which is as follows:

$$E = k_1 \frac{\sum k_{nm} \, a_{nm}^2}{|a_{n'm'}|} + k_2 L_t + k_3 \sum B_s + k_4 (I/N)^2 \tag{8}$$

where the first term is a weighted sum of spherical harmonics, the second term is an inductive term used when a shim or gradient magnet is being designed, the third term is a shielding term used when a shielded magnet of any type is being designed, and the fourth term is a power

term, mostly used for shim or gradient magnet design. In computing the first term, the summation does not include (n,m) = (n'm'). Other factors can be included in the error function if desired. The k_i's provide relative weighting between the various terms.

In equation 8, L_t is the total inductance of the magnet, I is the current which flows through all of the windings, and N is the total number of windings in the magnet. B_s is the field outside the shielding magnet and is typically summed at 100 points in the longitudinal direction and, if desired, at an additional 100 points in the transverse direction.

Of critical importance to the design of novel magnets is the first term of the error function. The k_{nm} coefficients of this term provide relative weightings to the spherical harmonic components generated by the magnet. In this way, desired harmonic components can be emphasized and undesirable components de-emphasized.

For example, for a superconducting magnet, it is usually desirable that harmonics above order 4 be more heavily emphasized than lower orders in the error function so that the contribution of these higher orders to the final field will be minimized by the basic design of the magnet. The lower order harmonics may end up to be larger than desired with such an error function, but these

harmonics can be compensated for in the shimming process or in further optimization runs. In particular, it is easier to null lower orders by shimming than it is to null higher orders.

5   Similarly, in the case of a gradient magnet, it is usually desirable that higher odd orders are emphasized in the error function because of their strong impact on the purity of the gradient. Along the same lines, in the case of a shim magnet, it is often desirable to emphasize 10 harmonics on either side of the harmonic to which the shim is directed to increase the purity of the correction. Importantly, by such relative weighting, it is possible to strongly reduce the B_0 harmonic of a shim magnet, thereby reducing frequency shifts upon shim activation, an 15 important result which has proved difficult to achieve with prior approaches to the design of shim magnets.

The $a_{n'm'}$ coefficient which appears in the denominator of the first term of the error function serves to further emphasize the most desired harmonic of the magnet which is 20 being designed. Because this coefficient is in the denominator, the error function is reduced when this coefficient increases. Therefore, the simulated annealing process will tend to increase the value of this coefficient. For a superconducting magnet, this 25 coefficient corresponds to the B_0 harmonic; for gradient

magnets, this is a first order harmonic; and for shim magnets, it can be of any order depending upon the shim under design.

Perturbation of the magnet design can be performed in various ways. A preferred procedure is to change each of the perturbation parameters by a random amount up to a maximum of, for example, 5% of a maximum allowable value for the parameter, each parameter having a different maximum allowable value. For example, in the case of coil locations, the maximum pertubation of any coil location can be constrained to be less than about 6 cm for an overall magnet length of 1.2 meters. Other maximum allowable perturbation values can, of course, be used if desired. It should be noted that if two coils end up to have a substantial overlap as a result of perturbations, it is usually convenient to have the procedure automatically coalesce the two coils into one.

After perturbation of the magnet structure and recalculation of the fields, harmonic components, and error function, a comparison is made between the value of the error function after the perturbation and the value which existed before the perturbation. If the value of the error function after the perturbation is smaller than that before perturbation the new arrangement of the magnet system is accepted (see box 42 of Figure 4). Positive

error excursions are also accepted based on a comparison of a random variable with the pseudo-Boltzmann function $\exp(-dE/T)$, where dE is the change in the error function and T is a "temperature" variable. This procedure of

5   accepting positive error excursions is termed the "Metropolis algorithm" (see box 44 of Figure 4).

If T is set very high relative to dE then the system will almost never accept positive dE excursions and conversely if T is small, the probability of positive dE

10   acceptance is high. In practice, T is selected to roughly equal the first dE following perturbation of the initial guess. Other selections of T are, of course, possible.

After a set number of perturbations chosen in the annealing schedule (box 30 in Figure 3), T is lowered and

15   the perturbation is continued (see boxes 48-52 of Figure 4). Two strategies are used for selecting when T is lowered. The first strategy (box 48 in Figure 4) counts the number of successful perturbations, i.e., a negative dE or an acceptable positive dE based on the Metropolis

20   algorithm, and lowers T when that number exceeds the predetermined value set in the annealing schedule. The second strategy (box 50 in Figure 4) simply counts the number of perturbation attempts, whether successful or not, and lowers T when the number of attempts exceeds a

25   predetermined value also set in the annealing schedule.

A maximum number of temperatures is also chosen in the annealing schedule, as well as a temperature reduction factor for each temperature drop.

For example, the maximum number of temperatures could be 50, the maximum number of attempts before a temperature drop could be 40, the maximum number of successful perturbations before a temperature drop could be 20, and the temperature reduction factor could be 0.9 times the current temperature. It is important that the temperature be reduced slowly so that the system does not quench (become trapped in a local minimum). At the stage when no successes can be found within the parameters of the annealing schedule at a particular temperature the system is said to be frozen (see box 32 in Figure 3 and box 60 in Figure 4).

In order to increase the speed of the computations, adaptive step sizing can be employed in accordance with the procedures discussed in Corana A, Marchesi M, Martini C and Ridella S 1987 Minimizing multimodal functions of continuous variables with the simulated annealing algorithm *ACM Trans. Soft.* 13 262-280. (See box 52 in Figure 4.) In accordance with this approach, at the end of each temperature cycle the step size is adjusted so as to maintain the ratio of accepted system perturbations to attempted perturbations at approximately 0.5. By means of

this approach, it has been found that the speed with which the location of a global minimum is found can be increased by up to 30%.

Boxes 54 and 56 of Figure 4 represent an optional procedure in which the temperature may be occasionally increased as part of the annealing schedule to ensure that a global minimum is eventually reached. The temperature increase can be, for example, between about 1.1 and about 2.0, e.g., 1.5, of the current temperature and may be performed randomly as the simulated annealing takes place.

The process of the invention as described above is preferably practiced on a digital computer system configured by suitable programming to perform the various computational steps. The programming can be done in various programming languages known in the art. A preferred programming language is the C language which is particularly well-suited to performing scientific calculations. Other languages which can be used include FORTRAN, BASIC, PASCAL, C^{++}, and the like. The program can be embodied as an article of manufacture comprising a computer usable medium, such as a magnetic disc, an optical disc, or the like, upon which the program is encoded.

The computer system can comprise a general purpose scientific computer and its associated peripherals, such

as the computers and peripherals currently being manufactured by Digital Equipment Corporation, IBM, Hewlett-Packard, Sun MicroSystems or the like.

Preferably, the processing portion of the computer system should have the following characteristics: a processing rate of 25 million floating point operations per second; a word length of 32 bits floating point, at least sixty four megabytes of memory, and at least 100 megabytes of disk storage. As discussed above, the system should include means for inputting data and means for outputting the results of the magnet design both in electronic and visual form. The output can also be stored on a disk drive, tape drive, or the like for further analysis and/or subsequent display.

Without intending to limit it in any manner, the present invention will be more fully described by the following examples. The wire diameter used in the examples was 1 mm. Other diameter wire could, of course, be used if desired. Also, different diameter wires can be used for different coils in the same magnet if desired to, for example, reduce mechanical stresses in the magnet.

Example 1

Shielded Superconducting Magnet

Using the simulated annealing procedures described above, a shielded, whole body superconducting magnet of

restricted overall length, specifically, 1.12 meters, was designed. The magnet coils were circular in shape and had a specified minimum inner diameter of about 90 cm. The weighting coefficients used in equation 8, the initial

5   guess, and the annealing schedule are set forth in Table 2.

Figure 5 is a plot of the progress of the value of the error function during the optimization process. This figure illustrates the effectiveness of the procedure in

10   reducing the error in a practical number of iterations. It further illustrates the acceptance of positive error excursions needed for the location of a global minimum in the annealing process. It should be noted that the annealing process was performed only on half of the

15   magnet, e.g., the right hand half, in view of the magnet's symmetry about z=0.

Figures 6 and 7 show the overall structure of the final magnet design. In particular, Figure 6 shows that the final design included 12 primary coils and 4 shielding

20   coils. It should be noted that this large number of coils were a result of the simulated annealing procedure and were not designated beforehand.

Figure 7 shows in greater detail, the upper right quadrant of the full magnet and indicates current flow

25   direction for the various coils. In accordance with the

invention, two of the primary coils shown in this figure have a reverse (minus) current flow. In other designs, it has been found that this reversal also occurs in some of the shielding coils as the overall length of the magnet is

5   further reduced, e.g., when the overall length is less than 1.0 meter in a whole body system. Similarly, for short overall lengths, it has been found that the number of coils in the shielding magnet tends to increase, e.g., to more than 4 coils.

10   The number of windings for the various coils (see Figure 6 for numbering) were approximately 172, 15, 373, 684, 526, 1347, 123, and 968 for coils 1 to 8, respectively. The magnet was designed on the assumption that the current flowing through the coils was 300

15   amperes.

Table 3 shows the harmonic deconvolution of the resultant magnet field produced by the magnet of Figures 6 and 7 when run at a current of 300 amps and deconvolved over a volume of 45×10^3 cm^3. As shown therein, the

20   homogeneity of the B_0 field is less than 20 ppm over this volume even though the magnet's overall length is less than 1.2 meters. This is a surprising result of the simulated annealing procedure of the invention.

The magnet system also exhibits excellent shielding

25   as evidenced by the fact that the 5 gauss stray field

location was at about 3.0 meters transversely and 2.5 meters longitudinally from the magnet isocenter, both of which are considered to be reasonably short distances for a whole body superconducting magnet system.

5   Figure 8 shows another superconducting magnet design developed in accordance with the simulated annealing procedure of the invention. This figure also shows the relationship of the magnet to the other components normally found in an MRI machine. Specifically, such a

10   machine includes neck tube 62, liquid nitrogen vessels 64, super insulation 65, liquid helium vessels 66, and vacuum chamber 68. The patient aperture is identified by the reference number 70 in this figure, and the primary and shielding coils by 72 and 74, respectively.

15   <u>Example 2</u>

<u>Comparative Example</u>

This example illustrates the importance of using a sum of weighted spherical harmonics in the error function of the simulated annealing procedure as opposed to using

20   an unweighted sum of such harmonics.

Two annealing procedures were performed for a superconducting magnet of the type discussed in Example 1. Table 4 sets forth the weighting coefficients used for the first annealing procedure; for the second annealing

procedure, all the weighting coefficients were set equal to 1.0.

The results of this comparison are shown in Figure 9, where relative field strength is plotted along the vertical axis and harmonic components along the horizontal axis. As can be seen in this figure, the procedure using weighted coefficients produced smaller strengths for the higher order harmonics than produced by the unweighted procedure, as is desired.

The first procedure produced a Z2 harmonic whose strength was greater than that produced by the second procedure. This harmonic, however, can be easily nulled by a shim magnet. Alternatively, further application of the simulated annealing procedure of the invention can reduce the magnitude of this harmonic without significantly corrupting the values for higher harmonics (see Example 1).

Example 3

Biplanar Superconducting Magnet

This example illustrates the design of a biplanar superconducting magnet using the simulated annealing procedures of the invention. As discussed above, such a magnet allows the sample, e.g., the patient, to be introduced into the magnet's homogeneous region along an

axis orthogonal to the longitudinal axis of the magnet's coils.

Figures 10A and 10B are perspective and cross-sectional views of the resulting magnet coils 76. The dimensions, locations, number of windings, and current directions for the various coils making up the magnet are set forth in Table 5. Only 6 of the 12 coils are described in this table due to the symmetry of the magnet. The terminology used in the table is as follows: "height" refers to the distance from the isocenter to the middle of each coil in the vertical direction; "radius" refers to the radius of the center of each coil; "layers" refers to the number of layers of windings in each coil; and negative windings indicate reversed winding direction, i.e., reversed current flow. As shown in this table, the magnet has an overall height of about 1.4 meters, an aperture height of about 1.1 meters, and a width of about 1.9 meters.

Table 6 shows the performance achieved by the magnet in terms of spherical harmonic components. As shown in this table, the magnet has a homogeneous region (20 ppm in B_0) whose volume is approximately 45×10^3 cm^3.

Example 4

Shim Magnet

Figures 11A to 11D show exemplary wire positions for various shim magnets designed in accordance with the invention. Dots in these figures indicate coils of maximum width 3 mm (i.e., three wires); if there are more than three windings in each coil (i.e., each dot) further layers are wound radially. This distribution is included in the simulated annealing process. Widths other than 3 mm can be chosen depending on the desired properties of the shim magnet under design.

Figure 11A shows the primary of a Z0 shim, Figure 11B, the shield for the Z0 shim, Figure 11C, the primary of a Z2 shim, and Figure 11D, the primary of a Z4 shim. The technique was also used to design Z1 and Z3 shims. It should be noted that a Z1 shielded shim magnet can be used as a longitudinal gradient magnet.

Table 7 shows the purity of shim magnets designed in accordance with the invention. As shown therein, the magnets exhibit a ratio of about 1,000 or more between the magnitude of the desired harmonic and the sum of the magnitudes of neighboring harmonics. This ratio exists over a region (the "zonal region") whose length/diameter ratio is less than 2. For shim magnets having an overall size suitable for use in whole-body imaging, this level of

purity is achieved for zonal regions having volumes greater than 45 x 10^3 cubic centimeters.

Figure 12 is a contour plot of field strength for the ZO shim magnet. The contour levels are shown at 0.01% intervals. The uniformity of the field produced by the magnet and the large volume over which the uniformity is achieved is evident in this figure.

Figure 13 is a plot of field strength versus longitudinal distance at a radial position of 1.0 cm outside the shield of the ZO shim magnet. The curve labelled A represents the unshielded field, and the curve labelled B shows the effect of shielding. The dramatic effect of the shielding is evident from these curves. Quantitatively, the calculated ratio of the rms shielded field to the rms unshielded field was less than 2%.

A ZO shielded shim magnet was constructed as per the winding arrangements of Figures 11A and 11B using conventional magnet construction techniques. Figure 14 shows a comparison of the predicted (curve A) and measured (curve B) field strengths along the longitudinal axis of the magnet. As can be clearly seen, the theoretical and actual field strengths are substantially the same. Quantitatively, the rms deviation of the difference between the two curves was less than 1%. The shielding achieved by the constructed magnet was also measured with

the shielding coils active and not active. The measured
ratio of the rms shielded field to the rms unshielded
field was 2.4%, which compares closely with the calculated
2.0% value discussed above.

5   Example 5

                        Shielding Magnet

          As discussed above in Example 1, it has been found
that as the length of a shielded superconducting magnet is
made shorter, the simulated annealing technique of the
10   invention results in magnet designs having (1) increased
numbers of shielding coils and (2) shielding coils with
reversed current flows.

          Figure 15 illustrates these effects for an initial
design of a short superconducting magnet. As in Figure 7,
15   Figure 15 shows only the upper right hand quadrant of the
magnet.   The coils having positive current flows are
indicated by plus signs in this figure. All other coils
have negative current flows.

          As shown in Figure 15, the techniques of the
20   invention have resulted in a shielding coil design which
for the full magnet employs 8 coils, two of which have
positive current flows, i.e., current flows opposite to
the normal current flow direction for a shielding magnet.

          Although preferred and other embodiments of the
25   invention have been described herein, further embodiments

may be perceived by those skilled in the art without departing from the scope of the invention as defined by the following claims.

TABLE 1

Order (n)	Degree (m)	Function	Name
1	0	Z	Z
2	0	$Z^2 - (X^2 + Y^2)$	Z^2
3	0	$Z[2Z^2 - 3(X^2 + Y^2)]$	Z^3
4	0	$8Z^2[Z^2 - 3(X^2 + Y^2)] + 3(X^2 + Y^2)^2$	Z^4
5	0	$48Z^3[Z^2 - 5(X^2 + Y^2)] + 90Z(X^2 + Y^2)^2$	Z^5
1	1c	X	X
1	1s	Y	Y
2	1c	ZX	ZX
2	1s	ZY	ZY
3	1c	$X[4Z^2 - (X^2 + Y^2)]$	Z^2X
3	1s	$X[4Z^2 - (X^2 + Y^2)]$	Z^2Y
2	2c	$X^2 - Y^2$	$X^2 - Y^2$
2	2s	XY	XY
3	2c	$Z(X^2-Y^2)$	$Z(X^2 - Y^2)$
3	2s	ZXY	ZXY
3	3c	$X(X^2 - 3Y^2)$	X^3
3	3s	$Y(3X^2 - Y^2)$	Y^3

The subscript "c" or "s" on the degree numbers indicates either cosine or sine azimuthal dependence.

TABLE 2A

Weighting Factors

k_1	$k_{2,0}$	$k_{4,0}$	$k_{6,0}$	$k_{8,0}$	$k_{10,0}$	$k_{12,0}$	$k_{14,0}$	k_2	k_3	k_4
1.0	0.2	0.4	0.7	0.8	1.0	1.0	1.0	0.0	0.8	0.1

TABLE 2B

Initial Guess*

Coil #	Axial Position (mm)	Width of Coil (mm)	Number of Turns	Base Radius (mm)
1	30	40	100	430
7	70	40	50	430
3	100	40	400	430
4	150	20	100	430
6	250	40	600	430
6	300	40	400	430
7	400	40	1000	430
8	100	80	-150	647
9	350	120	-850	647

*Axial position refers to the middle of each coil. Base radius refers to the radius on which the wire sits.

TABLE 2C

Annealing Schedule*

Maximum Number of Temperatures Tried	50
Maximum Number of Tries at Each Temperature	40
Maximum Number of Successful Perturbations Before Temperature Reduction	20
Temperature Reduction Parameter	0.9
Initial Temperature	2
Initial Step Size for Windings Per Coil	4%
Initial Step Size for Axial Position	2%
Initial Step Size for Radial Position	1.5%
Initial Step Size for Width of Coil	1%
Initial Number of Coils	20
Coalesce Coils If Overlap	yes
Step Adaptation	yes
Random Temperature Restart	yes
Restart Temperature Factor	1.5
Number of Restarts	4

*All initial step percentages refer to the physical constraints placed on each of the respective perturbation parameters.

TABLE 3

Harmonic	DSV-45cm (ppm)
Z_2	-2.1
Z_4	-0.19
Z_6	-0.8
Z_8	1.9
Z_{12}	3.8
Z_{12}	-4.5
Z_{14}	2.9
Z_0 (@ 300 A)	0.45T
half length	560 mm

DSV refers to the diameter of the homogeneous region.

TABLE 4

Weighting Factors

k_1	$k_{2,0}$	$k_{4,0}$	$k_{6,0}$	$k_{8,0}$	$k_{10,0}$	$k_{12,0}$	$k_{14,0}$	k_2	k_3	k_4
1.0	0.1	0.8	0.8	0.8	1.0	1.0	1.0	0.0	0.0	0.0

TABLE 5

Coil #	Height (mm)	Radius (mm)	Layers	Number of Windings
1	591.9	975.4	9.1	4187
2	630.1	781.5	13.7	-442
3	634.2	465.3	16.9	297
4	675.5	440.2	31.3	-372
5	644.1	156.1	16.1	74
6	682.3	172.3	17.6	265

TABLE 6

Harmonic	DSV-45cm (ppm)
Z_2	6.4
Z_4	1.3
Z_6	-3.6
Z_8	0.41
Z_{10}	0.67
Z_{12}	-2.1
Z_{14}	-5.9
Z_0 (@ 300 A)	1.0T

DSV refers to the diameter of the homogeneous region.

TABLE 7

Zonal Harmonic name	Z0 Value (mT)	Z1 Value (mT)	Z2 Value (mT)	Z3 Value (mT)	Z4 Value (mT)
Z0	**100.0**	0.0	-0.035	0	0.104
Z1	0	**100.0**	0.004	0.135	0
Z2	0.158	0	**100.0**	0	0.297
Z3	0	-0.189	0.0007	**100.0**	0
Z4	-0.185	0	-0.146	0	**100.0**
Z5	0	-0.029	0	-0.12	0
Z6	0.0206	0	0.017	0	0.085

All deconvolutions have been normalized to 100 for the dominant harmonic.

Tesseral harmonics are not shown as they were all $< 10^{-4}$.

What is claimed is:

1. A magnetic resonance system comprising a superconducting primary magnet which produces a magnetic field which is substantially homogeneous over a predetermined region (the "homogeneous region"), said magnet having a longitudinal axis and comprising a plurality of current carrying primary coils which surround the axis, wherein (i) the primary coils have a non-stacked configuration, (ii) the current in at least one of the primary coils is in an opposite direction to the current in an adjacent primary coil, and (iii) the current in at least one of the primary coils is in the same direction as the current in an adjacent primary coil.

2. The magnetic resonance system of Claim 1 wherein the length of the primary magnet along the longitudinal axis is less than about 1.5 meters.

3. The magnetic resonance system of Claim 1 wherein the length of the primary magnet along the longitudinal axis is less than about 1.2 meters.

4. The magnetic resonance system of Claim 2 or 3 wherein the magnitude of the variation of the magnet field in the homogeneous region is less than about 20 parts per million prior to any shimming and the homogeneous region has a volume which is greater than about 40×10^3 cubic centimeters.

5. The magnetic resonance system of Claim 2 or 3 wherein the magnitude of the variation of the magnet

field in the homogeneous region is less than about 20 parts per million prior to any shimming and the homogeneous region has a volume which is greater than about 45 x 10^3 cubic centimeters.

6.   The magnetic resonance system of Claim 1 wherein the number of primary coils is greater than six.

7.   The magnetic resonance system of Claim 1 wherein the system comprises a plurality of current carrying shielding coils which surround the primary magnet and wherein the current in at least one of the shielding coils is in an opposite direction to the current in at least one other of the shielding coils.

8.   The magnetic resonance system of Claim 7 wherein the overall length of the shielding coils along the longitudinal axis is no longer than the overall length of the primary magnet along said axis.

9.   The magnetic resonance system of Claim 8 wherein the overall length of the primary magnet along the longitudinal axis is less than about 1.5 meters.

10.   The magnetic resonance system of Claim 1 wherein the system comprises a plurality of current carrying shielding coils which surround the primary magnet and wherein the number of shielding coils is greater than four.

11.   The magnetic resonance system of Claim 10 wherein the overall length of the shielding coils along

the longitudinal axis is no longer than the overall length of the primary magnet along said axis.

12. The magnetic resonance system of Claim 11 wherein the overall length of the primary magnet along the longitudinal axis is less than about 1.5 meters.

13. A magnetic resonance system comprising a shim magnet which produces a magnetic field over a predetermined region (the "zonal region") which can be expressed as a sum of a predetermined number of zonal harmonics, said shim magnet having a longitudinal axis and comprising a plurality of windings, each of said windings surrounding the axis, wherein the length of the magnet along the longitudinal axis is less than about 1.5 meters, and the ratio of the magnitude of one of the zonal harmonics to the sum of the magnitudes of the other zonal harmonics is about a thousand or more and the zonal region has a volume which is greater than about 40 x 10^3 cubic centimeters.

14. The magnetic resonance system of Claim 13 wherein the length of the magnet along the longitudinal axis is less than about 1.2 meters.

15. The magnetic resonance system of Claim 13 wherein the ratio of the magnitude of one of the zonal harmonics to the sum of the magnitudes of the other zonal harmonics is about a thousand or more and the zonal region has a volume which is greater than about 45 x 10^3 cubic centimeters.

16. The magnetic resonance system of Claim 13 further comprising a shielding magnet for the shim magnet.

17. A method for improving the homogeneity of the magnetic field produced by the primary magnet of a magnetic resonance system, said primary magnet comprising a plurality of primary coils, said method comprising (i) arranging the primary coils in a non-stacked configuration, (ii) causing the current in at least one of the primary coils to flow in an opposite direction to the current in an adjacent primary coil, and (iii) causing the current in at least one of the primary coils to flow in the same direction as the current in an adjacent primary coil.

18. A method for designing a magnet system, said system having a longitudinal axis and comprising a plurality of current carrying coils, said method comprising:

(a) inputting data to a computer system regarding the length of the magnet system along the longitudinal axis; and

(b) determining a structure for the magnet system by performing a simulated annealing procedure using the computer system wherein the simulated annealing procedure employs an error function and the error function comprises a weighted sum of a predetermined number of computed spherical harmonic components of a computed magnetic field for the magnet system.

19. A method for producing a magnet system comprising:

(a) designing the magnet system by performing a simulated annealing procedure using a computer system wherein the simulated annealing procedure employs an error function and the error function comprises a weighted sum of a predetermined number of computed spherical harmonic components of a computed magnetic field for the system; and

(b) producing the magnet system designed in step (a).

20. The method of Claim 18 or 19 wherein the weighted sum of computed spherical harmonic components is given by:

$$\Sigma \ k_{nm} \ (a_{nm})^2$$

where k_{nm} are weighting coefficients, the a_{nm} are computed coefficients of a spherical harmonic expansion of the computed magnetic field, n is the order of the spherical harmonic, and m is the degree of the spherical harmonic.

21. The method of Claim 18 or 19 wherein the weighted sum of computed spherical harmonic components is given by:

$$\Sigma \ (k_{nm}/|a_{n'm'}|) \ (a_{nm})^2$$

where k_{nm} are weighting coefficients, the a_{nm} are computed coefficients of a spherical harmonic expansion of the computed magnetic field, n is the order of the spherical harmonic, m is the degree of the spherical

harmonic, $a_{n'm'}$ is a selected computed coefficient of the spherical harmonic expansion, and the summation does not include $(n,m) = (n',m')$.

22. The method of Claim 18 or 19 wherein the weighting of at least some of the lower order spherical harmonics is less than the weighting of at least some of the higher order spherical harmonics included in the error function.

23. The method of Claim 18 or 19 wherein the error function includes the Z2 spherical harmonic and the weighting of that harmonic is less than the weighting of at least one other spherical harmonic included in the error function.

24. The method of Claim 18 or 19 wherein the magnet system comprises a first magnet and a second magnet for shielding the first magnet and wherein the error function includes a shielding term.

25. The method of Claim 24 wherein the first magnet has a longitudinal axis and the error function comprises a first term representative of the magnetic field generated outside of the second magnet in a direction along the longitudinal axis and a second term representative of the magnetic field generated outside of the second magnet transverse to the longitudinal axis.

26. The method of Claim 18 wherein each of the plurality of current-carrying coils comprises at least one winding, and step (b) comprises at least one of (i)

determining the number of coils, (ii) determining the axial and radial location of the coils with respect to the longitudinal axis, (iii) determining the number of windings for the coils, and (iv) determining the direction of current flow in the coils.

27. The method of Claim 19 wherein the magnet system has a longitudinal axis and comprises a plurality of current-carrying coils, each coil having at least one winding, and step (a) comprises at least one of (i) determining the number of coils, (ii) determining the axial and radial location of the coils with respect to the longitudinal axis, (iii) determining the number of windings for the coils, and (iv) determining the direction of current flow in the coils.

28. The method of Claim 26 or 27 wherein the current in at least one of the coils is in an opposite direction to the current in at least one other of the coils.

29. The method of Claim 18 or 19 wherein the magnet system comprises a primary magnet of a magnetic resonance system.

30. The method of Claim 29 wherein the magnet system further comprises a shielding magnet for the primary magnet.

31. The method of Claim 18 or 19 wherein the magnet system comprises a shim coil of a magnetic resonance system.

32. The method of Claim 31 wherein the magnet system further comprises a shielding coil for the shim coil.

33. The method of Claim 31 wherein the shim coil is associated with a particular spherical harmonic and the weighting of that harmonic in the error function is substantially smaller than the weighting of all other harmonics included in the error function.

34. The method of Claim 18 or 19 wherein the magnet system comprises a magnetic resonance system which comprises a gradient coil and a shielding coil for the gradient coil.

35. A method for designing a magnet system, said system having a longitudinal axis and comprising a first magnet and a second magnet for shielding the first magnet, said method comprising:

(a) inputting data to a computer system regarding the length of the magnet system along the longitudinal axis and at least one characteristic dimension of the first magnet in a direction orthogonal to the longitudinal axis; and

(b) determining a structure for the magnet system by performing a simulated annealing procedure using the computer system wherein the simulated annealing procedure employs an error function and the error function comprises a first term representative of the magnetic field generated outside of the second magnet in a direction along the longitudinal axis and a second

term representative of the magnetic field generated outside of the second magnet transverse to the longitudinal axis.

36. The method of Claim 35 including the additional step of producing the magnet having the structure determined in step (b).

37. A method for designing a magnet system, said system having a longitudinal axis and comprising a plurality of current carrying coils which surround the axis, said method comprising:

(a) specifying in a computer system that the magnet has at least six coils and at least one coil wherein the current is in an opposite direction to the current in at least one other coil; and

(b) determining a structure for the magnet system subject to the specifications of step (a).

38. The method of Claim 37 wherein the maximum internal diameter of the coils of the magnet is D, the length of the magnet along the longitudinal axis is L, and the ratio of L/D is less than about 1.5.

39. The method of Claim 37 wherein step (b) is performed by solving a set of simultaneous equations in Legendre polynomials.

40. The method of Claim 37 including the additional step of producing a magnet having the structure determined in step (b).

41. A magnet system designed by the method of Claim 18.

42. A magnet system produced by the method of Claim 19.

43. A magnet system designed by the method of Claim 35.

44. A magnet system produced by the method of Claim 36.

45. A magnet system designed by the method of Claim 37.

46. A magnet system produced by the method of Claim 40.

47. Apparatus for designing a magnet system comprising a programmed computer for designing the magnet system by performing a simulated annealing procedure wherein the simulated annealing procedure employs an error function and the error function comprises a weighted sum of a predetermined number of computed spherical harmonic components of a computed magnetic field for the system.

48. An article of manufacture comprising a computer usable medium having computer readable code means embodied therein for designing a magnet system by performing a simulated annealing procedure wherein the simulated annealing procedure employs an error function and the error function comprises a weighted sum of a predetermined number of computed spherical harmonic components of a computed magnetic field for the system.

49. A magnetic resonance system comprising:

a superconducting primary magnet having a longitudinal axis and comprising a plurality of current carrying primary coils which surround the axis, wherein (i) the primary coils have a non-stacked configuration, (ii) the current in at least one of the primary coils is in an opposite direction to the current in an adjacent primary coil, and (iii) the current in at least one of the primary coils is in the same direction as the current in an adjacent primary coil; and

a superconducting shielding magnet comprising a plurality of current carrying shielding coils which surround the primary magnet, wherein (i) the current in at least one of the shielding coils is in an opposite direction to the current in an adjacent shielding coil, and (ii) the current in at least one of the shielding coils is in the same direction as the current in an adjacent shielding coil.

50. The magnetic resonance system of Claim 49 wherein the number of primary coils is greater than six.

51. The magnetic resonance system of Claim 49 wherein the number of shielding coils is greater than four.

52. The magnetic resonance system of Claim 49 wherein the overall length of the shielding coils along the longitudinal axis is no longer than the overall length of the primary magnet along said axis.

53. The magnetic resonance system of Claim 52 wherein the overall length of the primary magnet along the longitudinal axis is less than about 1.5 meters.

54. The magnetic resonance system of Claim 52 wherein the overall length of the primary magnet along the longitudinal axis is less than about 1.2 meters.

55. A magnetic resonance system according to claim 1 and substantially as herein described.

The Patent Office

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Application No: GB 9625474.3	**Examiner:** K. Sylvan
Claims searched: 1-12,17,49-55	**Date of search:** 14 February 1997

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): G1N (NG38,NG38A,NG40)

Int Cl (Ed.6): G01R (33/38,33/3815,33/3875)

Other:

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
X	GB2070254 A Oxford Instruments. See figure 3.	1,17,49 at least
A	EP0304188 A2 GE. See page 9 lines 16-18.	-
X,P	WO96/13045 A1 Sandia. See page 27 lines 35-38.	1,17,49 at least
X	WO 94/06034 A1 GE. See page 5 lines 29-31.	1,17,49 at least
A	US4398150 Thomson. See column 3 lines 28-31	-

X	Document indicating lack of novelty or inventive step	A	Document indicating technological background and/or state of the art.
Y	Document indicating lack of inventive step if combined with one or more other documents of same category.	P	Document published on or after the declared priority date but before the filing date of this invention.
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